COOK INLET SEDIMENT BUDGET AND WATER QUALITY MODEL

By

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Abstract

The topic that is being addressed is whether the sediment load into Cook Inlet increasing as the glacier melt rate has increased in the last 50 years?

This is important since regional watershed understanding of the sediment balance and potential changes in sediment erosion and deposition rates in areas and along the coast may impact infrastructure like pipelines, bridges and roads, or communities.

The scope includes a discussion on over fifty (50) years of related research, river water and sediment inputs, and an assessment of existing models. Data from USGS and other available sources were gathered, a large scale, high-level statistical assessment was conducted to determine if the riverine discharge data showed any significant increases in flow and sedimentation. The initial results showed that flow was increasing in time, and sediment transport could be as well. A more comprehensive review of the riverine discharge data shows a trend that the rivers are experiencing larger flows. There is not sufficient, comparable data yet to determine if the sediment load has also increased. The research efforts helped to create a basic sediment budget for the Cook Inlet Watershed.

The most important results are that the glaciers are melting at a faster rate and the data show that the river discharge volumes are increasing, while sediment rates remain constant or are decreasing. The question this thesis is attempting to answer is whether there is also an increase in the sediment transport. Based on the available data reviewed, the river sediment load appears to be decreasing while the river water content appears to be steady or increasing.

Preface

This effort started while drafting of the Cook Inlet Oil and Gas Exploration permit Ocean Discharge Criteria Evaluation. Instead of a single volume or model providing a comprehensive view of all the combined discharges in the area, along with the natural variations in water density due to salinity and sediment, decades of research papers and reports were reviewed. A full understanding of the sediment balance and potential changes in sediment erosion and deposition rates had not been published. This information impacts communities and infrastructure like pipelines, bridges and roads. Proposed discharge modeling focuses on small areas, based on density driven diffusion. Lacking density data, the search moved to stratification. Stratification occurs when the freshwater input from the glaciers and rivers into the upper Cook Inlet, typically sediment rich and less dense, meets the denser, cooler saltwater being pushed up by the tide from the Gulf of Alaska. While these dynamics have been documented, no detailed or multi-variable model existed at the time for the upper Cook Inlet depth-varied space.

At the time, the research focus was on potential amount of exploration drilling solids to be discharged into the waters and whether that volume could be considered significant. Roughly 40 million metric tons of glacial silt and sediment are moved annually by the Cook Inlet watershed and it was estimated that drilling discharges might be 1% of the natural sediment deposited from the rivers. This snapshot of information inspired more questions. During this time, a gas leak existed in one of the roughly 200 miles of subsea pipelines in Cook Inlet. This leak was likely caused by the migrating boulder waves, which are part of the local lore and have yet to be well documented.

The initial analysis was to determine if more sediment load in the Cook Inlet Watershed Rivers exists today than 50 years ago. However, once sediment research began in earnest, it became important to understand which rivers contribute the most sediment to the Cook Inlet Watershed. Further, does enough data exist to show that the amount of sediment is changing?

The overarching research has been working toward a computer model, intending to include salinity in a 3D model of the Cook Inlet that also accounts for sediment flow. To populate a computer model, aspects related to the watershed, realistic inputs and values from past evaluations were collected and model trials set. The next phase focused on ascertaining trends, and whether a small portion of that can be better understood and shared.

Acknowledgments

Michael Ulmgren graciously helped me to understand the model used for the basis of this thesis. He was also integral to my learning how to use Delft3D.

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The U.S. Geological Survey team has collected decades of data that are the basis of this research.

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The diligent efforts of the Cook Inlet Regional Citizens Advisory Council
The National Oceanic and Atmospheric Administration and their many data collection stations along with scientists developing models and deploying to gather additional information to better understand the elements and forces at work in Cook Inlet.

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Chapter 1: Introduction, problem statement and research objectives

1.1. Background

Alaska is home to many dynamic ecosystems, including glaciated mountain ranges (including the highest peak in North America, Denali), some of the largest river systems in North America, and much of the United States coastline. The Southcentral region of Alaska contains Cook Inlet, which sits at the mouth of the Susitna River and extends to the Shelikof Strait and the Gulf of Alaska. The mudflats of upper Cook Inlet (Knik and Turnagain Arms) are significant sedimentary features. The Knik and Turnagain mud flats, as well as the many river deltas comprising the upper region of Cook Inlet, are neither currently protected nor being pursued for development. The goal of this thesis is to model and evaluate whether transport rates of sediment from glacial inputs are increasing due to climate change. See Figures 1, 2, and 3 for an overview map of the Cook Inlet Watershed and region.

Cook Inlet is located near the population center of Alaska, including the city of Anchorage, and is home to extractive industries (mining and oil and gas development), a vital shipping channel and port, and diverse populations of wildlife. Over the past several decades some detailed studies have been completed regarding the dynamics of the water flow patterns and related management practices in the Inlet.

The water flow into the Cook Inlet is dynamic and directed by two main sources: the freshwater river inflow from the Susitna and Knik Rivers and the saline ocean flow from the Gulf of Alaska. Typically, the sediment-rich waters are brownish and grey, with a strong delineation visible from the air. The denser ocean water is deeper blue and comes into the Inlet along the western edge, leading north as suggested by Okkonen et al. (2009 [1] and Okkonen (2005) [2].

1.2. Problem Statement

The existing evaluations of the Cook Inlet Watershed and related models do not currently include both water quality and sediment inflow in relation to a sediment budget for annual or prolonged review of erosion and depositional variation. Many studies of the tidal forces, portions of sediment dynamics, and seasonal variations in water characteristics have been conducted. This thesis attempts to take a deeper look at the available data to assess trends in the watershed.

This thesis relies on these past studies as well as more updated modeling techniques with the goal of providing a more comprehensive overview of the water quality characteristics, tidal and circulations patterns, and sediment transport rates. Due to the limited amount of macrotidal investigations, it is critical to have effective coastal region prediction models that can simulate macro-tidal regions.

1.3. Research Objectives and Scope

This is a thesis for a Master of Science in Civil Engineering at the University of Alaska, Anchorage. The topics included are river and marine water quality, tidal and current influences, and sediment transport, and ultimately, also the review of computer models of Cook Inlet. The objective of this thesis is to quantify the sediment sources and dynamics in Cook Inlet, Alaska with a Sediment Transport Model of Cook Inlet, including Tidal Mud Flats and Water Quality. Cook Inlet is a tidally influenced waterbody connected to the Gulf of Alaska and multiple glacially fed rivers.

This thesis intends to quantify (via computer modeling validated with collected and available data) trends in glacial melt and river flow as well as the impact they have on sediment transport rates and related parameters in Cook Inlet. The riverine flow and sediment budget in Cook Inlet were reviewed, assessed, modeled, and evaluated based on coastal depositional rates, tidal forces, water quality parameters, and seasonal variability. As part of the thesis drafting process, studies completed over the last several decades were reviewed, including models developed in the recent past. Additional in-field samples were reviewed to build a reasonably representative model.

1.4. Potential Benefits

Over the last six to seven decades, multiple studies focusing on various aspects of Cook Inlet have been completed, most of which aimed to gain better understanding of circulation dynamics as part of the Oil and Gas industrial development of the region. Other studies focused on oil spill response (partially due to the Exxon Valdez tanker spill in Prince Willian Sound). As a result, many sources of data are available today to develop a sediment transport model that includes water quality and circulation details. What has been missing to date, is a reasonable mechanism to track glacial sediment flowing into Cook Inlet from the freshwater rivers, analysis and quantification of the sediment deposition and resuspension dynamics on the many acres of tidal mud flats, and a more complete view of the salinity gradients and stratification dynamics along Cook Inlet. Another way to refer to this is as a sediment budget. An increase in sediment flow may be related to an increase in glacial melting.

These sediment transport mechanisms are not currently well understood and have yet to be modeled, yet the Port of Anchorage's study related to annual port dredging activities implies that sediment flows into upper Cook Inlet may be increasing, according to Hayter and Smith (2012) [3]. The coastline of Knik Arm has been subject to erosion in the past few years. This could be leading to an increase in deposition on the mudflats. Some preliminary data collection and incorporation into a comprehensive Delft3D model may be helpful in gaining a more complete understanding of the water quality, salinity and sediment fate, and transport dynamics in Cook Inlet. Figures 1 and 2 show satellite images of the confluence of lower and upper Cook Inlets. According to Oey et al. (2007), "saline water in the lower Cook Inlet and the brackish water from rivers and melting ice from around the upper Cook Inlet produces a salinity front" [4]. These can be seen in the Figures 1 and 2.

1.5. Thesis Organization

This thesis paper is organized into six primary chapters followed by References and Appendices.

Chapter 1 – Introduction, Problem Statement, and Research Objectives

Chapter 2 – Literature Review

Chapter 3 – Methodology

Chapter 4 – Analysis and Results

Chapter 5 – Summery of Findings

Chapter 6 – Conclusions and Recommendations

References and Appendices

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Figure 1: Satellite image of the confluence of lower and upper Cook Inlet [5]. Lower Cook Inlet's saline waters and muddy water from rivers and melting ice in upper Cook Inlet produces a salinity front. Some significant rivers and glacial headwaters are also shown.

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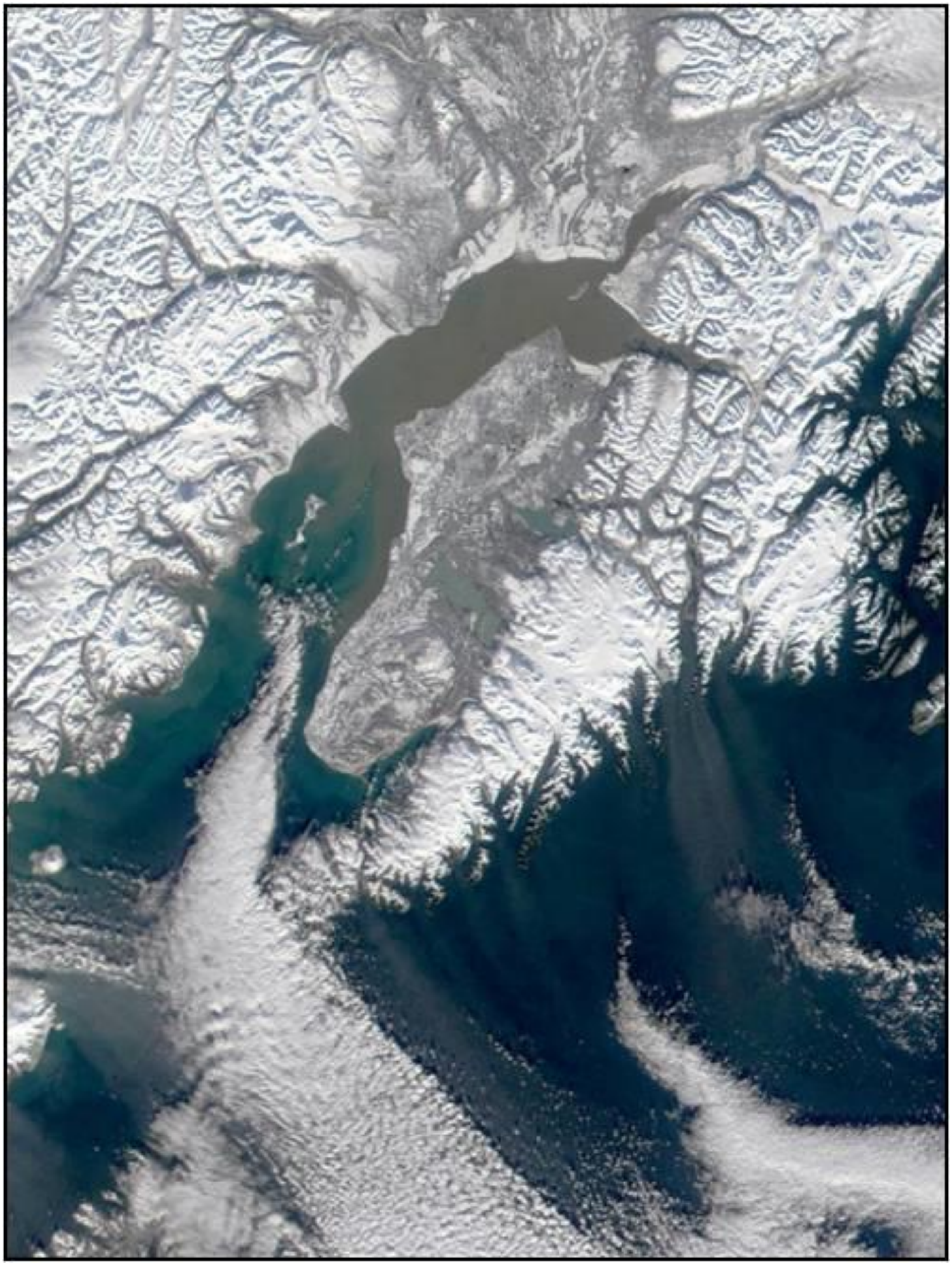


Figure 2: Aerial image of the major drainage areas of the Cook Inlet Basin, Alaska [6]. The band of white seen in Figure 2 over Lower Cook Inlet is clouds.

Chapter 2: Literature Review

The literature review section is separated out into three sections, starting with the regionally relevant literature to help set the stage and explain the location (Section 2.1). The next section (2.2) covers specific water dynamics and the related studies. The third and final section (2.3) focuses on sediment transport research and studies related to sediment transport in Cook Inlet.

2.1. Regional Relevance and Water Transport

Water-Quality Assessment of the Cook Inlet Basin, Alaska – Environmental Setting, USGS 1998-2001 (Glass et al., 2004)

This report serves as a comprehensive summary of the inputs for Cook Inlet in terms of watersheds, sediment load, and related human activity. See Figure 3 below for an overview of the watershed, which encompasses about 39,300 square miles (or about 101,800 km^2) [7]. According to Glass et al. [7], the data collected by USGS in-stream measurements and other sources, the average annual sediment input into Cook Inlet is 44,450,000 tons (40,404,041 metric tones) and the related water flow rate is 116,000 ft^3/s (3,285 m^3/s). This report served as an introduction to the watershed and rivers, discussing trace metal concentrations and sediment levels and their potential sources. The data used in this report, along with additional data from other sources, were reviewed and further analyzed as part of this thesis. This information supports the evaluation of river and sediment flow rate trends discussed later in the data assessment section.

Environmental Monitoring and Assessment Program (EMAP): Gulf of Alaska Sampling Effort (DEC, 2002) and Integrated Cook Inlet Environmental Monitoring Assessment Program (ICIEMAP) efforts regarding Cook Inlet sampling, (DEC and CIRCAC, 2008 & 2009)

The Department of Environmental Conservation (DEC) started collecting baseline data in 2001 with the Environmental Monitoring and Assessment Program (EMAP) to establish a water quality database for the coastal regions of Alaska [8]. The phase that was conducted in 2002 included the Gulf of Alaska and in 2008 and 2009 the Integrated Cook Inlet Environmental Monitoring Assessment Program assessed the Cook Inlet region. The data collected in Cook Inlet was part of a co-operative program with the Cook Inlet Regional Citizens Advisory Council (CIRCAC) [9]. They used the EMAP protocols for random sampling, which was a cost and time efficient method to capture a snap-shot of Alaska's coastal water and estuary conditions, as noted in Saupe et al. [8].

These data have been used in several other reports and are currently available to the public online via GIS mapping tools. The DEC Water Quality Standards, Assessment and Restoration Program has created a Water Quality Monitoring Map that is publicly available, as shown in Figure 4 below. The dots represent water quality monitoring data sets [10]. Drogues were used [9], which were incorporated into the model for additional water quality points and assist in delineation of salinity. This information is valuable to the development of an understanding of the water quality, stratification and seasonal variation in Cook Inlet. These values that were part of the data collection efforts were not greatly explored in the report as the focus was looking at how the waterbody compared to the state's water quality standards.

<u>Fate and Transport of Produced Water Report, (Kinnetic Laboratories, Inc., 2010)</u>

Cook Inlet is home to about 20 oil and gas production facilities whose discharges are regulated by an Alaska Pollutant Discharge Elimination System general permit. A requirement of a previous permit was for the companies that own and operate these oil and gas facilities to fund a comprehensive study in Cook Inlet to determine environmental impacts caused by their discharges. The study relied on previous water column and sediment sampling done by the Environmental Monitoring Assessment Program (EMAP) program (noted above) along with additional samples collected during 2008 through 2009. The report includes an evaluation of these samples with the overarching conclusion that any related environmental impact from the oil and gas operations was not apparent in the data collected. Other interesting aspects of the study include baseline samples in other, known depositional areas, and a discussion on what parameters are present and what the likely sources for these parameters are (via fingerprinting) [11]. This information, in conjunction with the data provided by the EMAP/ICEMAP reports is valuable to the development of an understanding of the water quality, stratification and seasonal variation in Cook Inlet. These values reports were not greatly explored in general by other studies, partially as they were focused on the wastewater discharge permit requirements. Since data was collected at various depths and in multiple locations, a more complete image of the varying densities and sediment concentrations was possible.

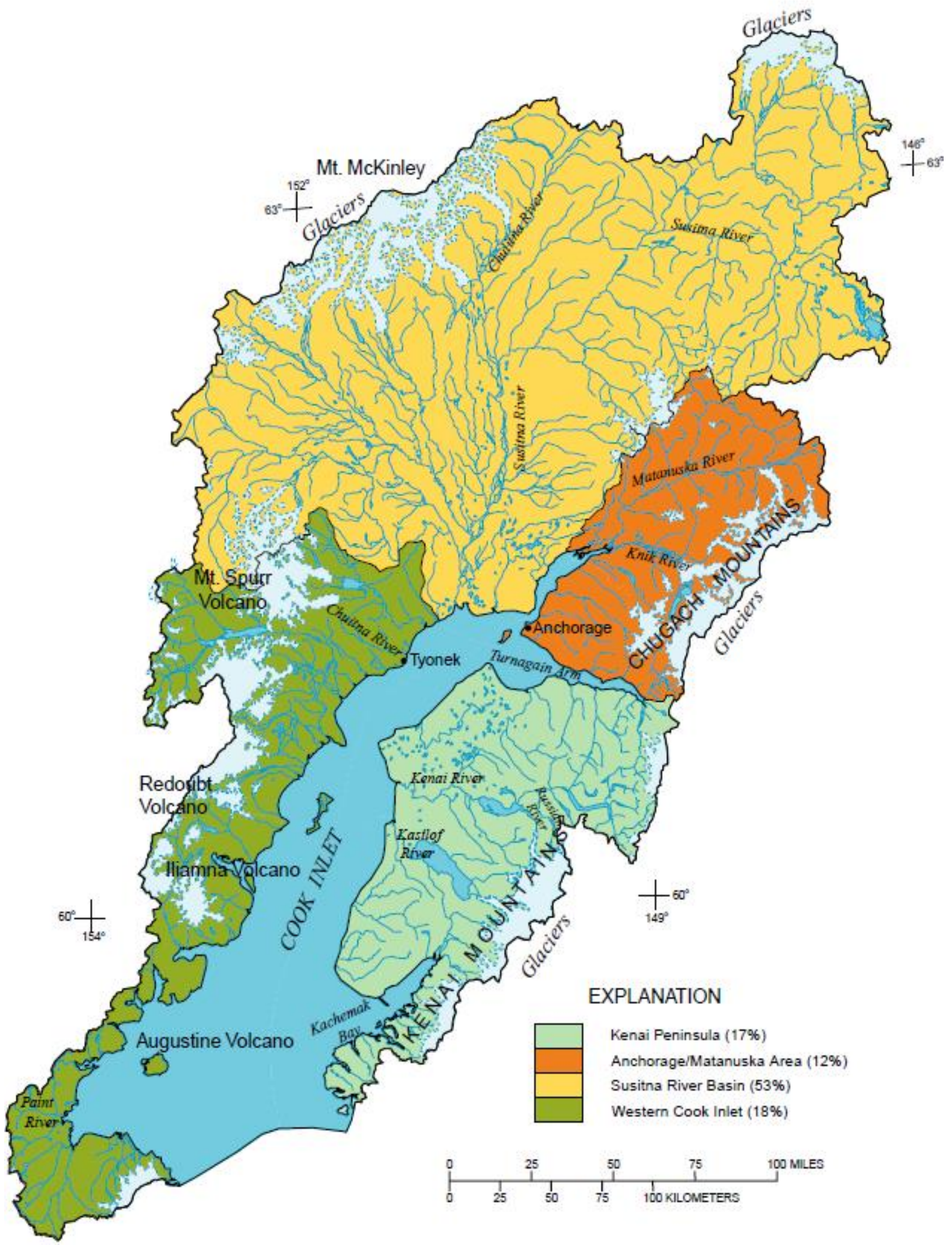


Figure 3: USGS regional overview and map of Cook Inlet Watershed with rivers from 2004 [7].

Figure 4: Alaska Department of Environmental Conservation (DEC) Water Quality Monitoring Map. The dots represent water quality monitoring datasets [10].

<u>Ocean Discharge Criteria Evaluation for Cook Inlet Offshore Oil and Gas Permit, (Alaska Department of Environmental Conservation, 2016)</u>

This technical review of the region and industrial impacts summarizes many scientific studies. Of interest is the discussion of the water sources, circulation patterns, and water quality details. In the Cook Inlet, most of the sediment is glacially sourced and heads with fresh water in a southeastern direction while the tides pull saline water from the Gulf of Alaska northward. The stratification in each area is dynamic, depending on water flow, wind, and related subsurface circulation. Additional sediment movement along the coast and through the Forelands further complicates a sediment budget view, with subtractions and additions happening continuously and the large tidal movements constrained at the Forelands allowing for the movement of large boulders [12].

The effect of the southeastern flow of freshwater and the northwestern flow of salt water creates a circular flow pattern in the Inlet and specific micro-ecosystems throughout. The upper Inlet, north of Fire Island, is relatively shallow, as are the bays and arms. Subsequently, water in the upper inlet is more often fresher and contains more suspended solids. The lower Cook Inlet, at the Forelands and further south, is relatively deep. As such, the water is generally cooler and more saline. The conditions and depth at the Shelikof Straits are such that a ship's inability to anchor in rough seas was of considerable concern. The general assumption is that the majority of the metric tons of sediment moved annually from the mountains, drops out by the time the water reaches the Straits [12] as the water is significantly deeper and less influenced by the tides, wind, and sediment is generally allowed to settle.

With over 50 years of data, gathered at depth, on shore, and at each platform, several snapshots in time are presented. The goals of each data collection effort and related report varied, from determining the required technology and location for platform placement to baseline establishment of the ecosystem to long-term impact trend evaluations. Consistently present were density readings (looking at both sediment and conductivity) and water temperature at depth. With these data, some seasonal interpretations of density stratification can be made [12].

The Cook Inlet area has three climate zones: maritime, continental, and transition. Mean temperatures range from the upper 50s° F (10° C) in the summer to the low 20s° F (–7° C) during the winter [12]. The upper Cook Inlet region is drier and cooler, while the lower Cook Inlet region is a maritime climate. Areas further from the coast may have continental zone characteristics, with annual precipitation from 10 to 15 inches (25.4 to 38.1 cm), mean temperature ranges from the upper 60s° F (15° C) in the summer to –10 to –30° F (–23 to –34° C) during the winter [12]. In northern Cook Inlet, precipitation usually falls as snow from October to April and as rain during the rest of the months. Farther south in Cook Inlet, a greater percentage of the precipitation falls as rain. The wettest months are September and October, with relatively dry conditions April through July. In Cook Inlet, precipitation increases from north to south, with annual precipitation averages about 60 inches (1.5 m) in the maritime zone areas, which encompass the coast and islands [12].

Winds in the area are strongly influenced by mountains surrounding the Cook Inlet basin. During the fall to spring months (September through April), the prevailing winds are typically from the north or northwest, with winter extremes of 50–75 knots (92–139 km/h, 84–125 ft/s). During the summer months (May through August), winds prevail from the south and offshore winds average 12–18 knots (22–33 km/h, 20–30 ft/s). Surface winds tend to be lighter compared to coastal maritime areas. Site- specific, short- term data confirm the general trends described above. Extreme winds are commonly out of the northeast or south [12].

When the tidal and freshwater flows interact with the bathymetry, convergence zones, or tidal rips, are formed. These are generally located above rapidly changing bathymetry and often delineate strong gradients in water properties, including temperature, salinity, and suspended sediments, and the current according to Oey, et al. [4], as well as Okkonen and Howell [13], Okkonen (2005) [2], Okkonen et al. (2009) [1]. There are three main rips that are often evident in central Cook Inlet. They extend from the vicinity of the Forelands to beyond the southern tip of Kalgin Island. During the stages of the tidal cycle when the rips are strongest, debris, ice, and spilled oil can accumulate along their axes, as stated by Johnson [14].

Some of the highest tidal amplitudes in the world can be found in the Cook Inlet basin. These are driven by the principal tidal influence of the lunar semidiurnal tide and the size, shape, and bathymetry of Cook Inlet, which create a funneling effect. At the mouth of Cook Inlet, the mean tidal range varies from 11 feet (3 m) at the Barren Islands to more than 27 feet (8 m) at Anchorage, as stated by Lanerolle and Patchen [15]. This large tidal exchange within Cook Inlet causes strong tidal currents, with an average maximum surface current of three knots (5.5 km/h, 5 ft/s) [12]. This information is valuable to the overall appreciation and perspective of both the physical setting where Cook Inlet lies and the characteristics that contribute to the watershed.

<u>Glacial Meltwater Input to the Alaska Coastal Current (Kipphut, 1990)</u>

This report evaluates the possible sources of glacial melt into the Gulf of Alaska (GOA) and estimates that the total meltwater inputs in 1982 and 1983 were 11,877 m^3/s and 17,765 m^3/s, respectively. These values are based on an assessment of the Columbia, Harvard, and Aialik glaciers. Kipphut's [16] report also includes a discussion of coastal precipitation and measurements in coastal waters. This report provided significant evidence that the freshwater input into the Alaska Coastal Current (ACC) comes from rivers. While the ACC is significantly south of the region of focus for this report in beyond the Shelikof Strait in the GOA, the information is still valuable as it provides a boundary to the sediment budget for the Cook Inlet watershed and some perspective on river flow quantities.

Assessing streamflow sensitivity to variations in glacier mass balance (O'Neel, et al., 2014)

This study utilizes a mass balance approach to better understand glacial melt cycles. The data analyzed are from two Alaskan glaciers, one continental (Gulkana) and one maritime (Wolverine), were used to assess if ocean or air warming may play a significant role in glacial melt rates. The authors also include an energy balance monitoring approach, which covers the glacier water balance budget by source and time. Based on the evaluations, models, and estimates of O'Neel, et al. [17], roughly 410 km^3/year of water melts from glaciers annually in Alaska, and this value constitutes about half of the total flow in streams [17]. The data considered in the report by O'Neel [18] covers almost 50 years of observations. This study is interesting since parallel assumptions borrowed from the glacial retreats can be applied to other glaciers in Alaska. In the case of the Cook Inlet watershed, the assumption used is that about 50% or more of the river discharge and sediment are glacially sourced. This information is valuable to the development of a sediment budget and the assumptions are carried into the values represented by the rivers.

Measurements of Temperature, Salinity and Circulations in Cook Inlet (Okkonen and Howell, 2003), Observations of Hydrography and Currents in Central Cook Inlet During Tidal Cycles (Okkonen, 2005), and Seasonality of Boundary Conditions for Cook Inlet, Alaska (Okkonen et al., 2009)

These three reports provide a significant portion of the data available for modeling the dynamics of Cook Inlet. These data related accurate numerical simulations of the hydrography circulations within Cook Inlet, and are summarized by five factors: (1) freshwater discharges, (2) heat and salinity fluctuations, (3) bathymetry, (4) tidal forces, and (5) solar insolation according to the following: Okkenen and Howell [19], Okkonen [2], and Okkonen, et al. [1]. The circulation of water in Cook Inlet is influenced by several factors, including the shape of the Inlet, bathymetry, and freshwater input from rivers, the Alaska Coastal Current (ACC), and tides. Okkenen, et al. [1] found that temperature and salinity gradients existed between lower and central Cook Inlet, between the east and west sides of the Inlet. This was evident from the hydrographic data that they acquired through this project [1].

Cook Inlet is a 217-mile (350-kilometer) long inlet that has a free connection to the open ocean and a general northeast to southwest orientation. It is divided naturally into the upper and lower regions by the East and West Forelands, where Cook Inlet is approximately 16 km (10 miles) wide. Cook Inlet, and its channels, coves, flats, and marshes, are a mixture of terrestrial sources from numerous river drainages and marine waters of the Shelikof Strait and the Gulf of Alaska. Cook Inlet varies in width from about 62 miles (100 km) near the entrance to less than 12 miles (20 km) at its head.

Cook Inlet is long and narrow. It has shoals towards its head where it separates into two narrow shallow arms (Knik and Turnagain). The East and West Forelands constrict water flow and influence the movement of water between central and upper Cook Inlet.

Rivers discharging into the upper inlet and along the west side make up the major freshwater inputs. It is likely that the ACC and these freshwater inputs account for most of the non-tidal influence on circulation in upper and middle Cook Inlet, except on the west side. The fresher water from the Upper Inlet flows south along the west side and it eventually meets with the westward-moving ACC near Augustine Island (Okkonen, et al., 2009) [1].

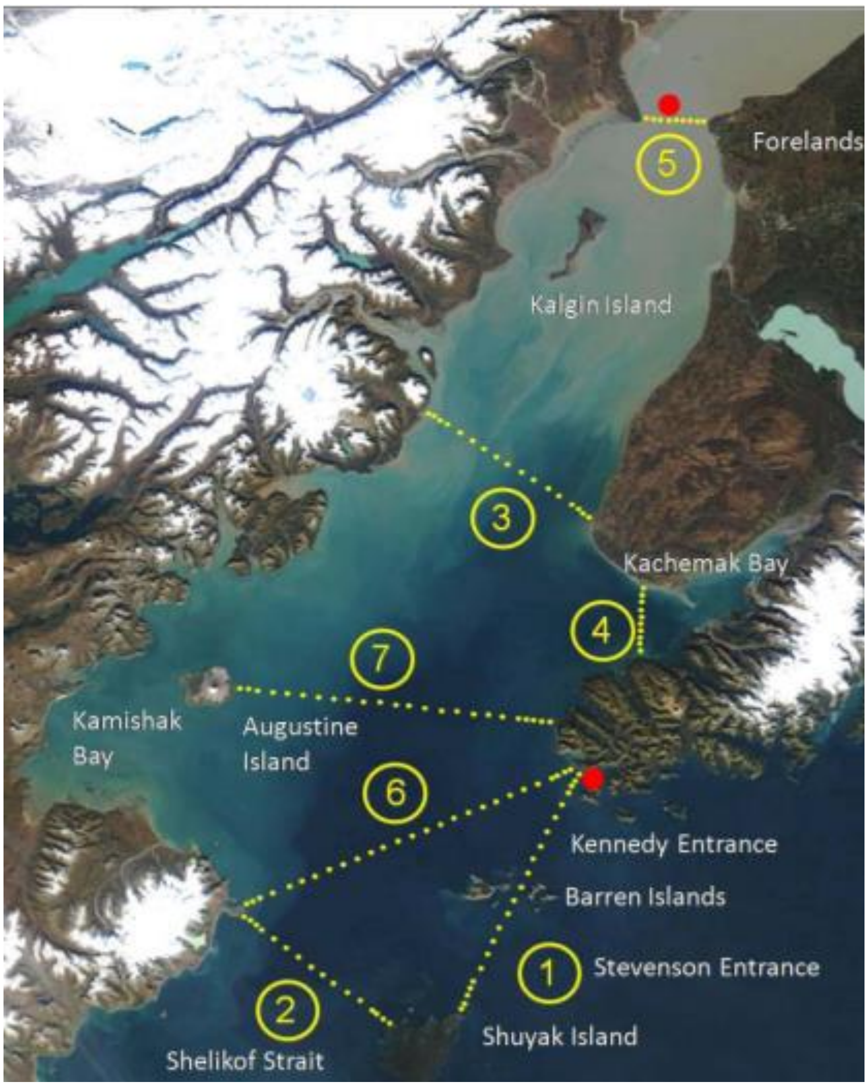


Figure 5: Cook Inlet transact map showing sediment rich and ocean water regions [1].

The northern edge of the ACC generally follows the 100-meter isobath around the mouth of Cook Inlet. The southward flowing water along the western boundary is generally trapped by the ACC. Most of the freshwater flow out of Cook Inlet narrows to a few kilometers in width as it passes Cape Douglas at the southern end of Cook Inlet (Okkonen and Howell 2003) [19].

This information is valuable to the overall understanding of the region and has been utilized and cited by many other studies. Their work provides significant insight into the regional and seasonal variabilities of density and the navigational hazards posed by the interfaces of circulation and tidal forces.

<u>Distribution of hydrocarbons and microbial populations related to sedimentation processes in Lower Cook Inlet & Norton Sound (Atlas et al. 1983)</u>

This report reviews river inputs and ocean conditions regarding the movement of sediment into and out of Cook Inlet and Norton Sound. Specific discussions by Atlas et al. [20] include sediment particle size, depositional areas, biological populations and activities, and any detectable organic carbon or hydrocarbon concentrations. The general discussion covers the settling velocities and likely deposition areas, as well as some of the sea floor depositional patters and sediment movement along the bottom of the water column. The overall conclusion is that most of the sediment likely slows down sufficiently in the deeper water near Shelikof Strait and is deposited [20]. This study was part of a deeper look into the possible impacts of hydrocarbon production in Cook Inlet and the surrounding waterbody. Their seafloor assessments and particle size discussions lead to the settling velocities and general understanding of the sediment budget for the watershed.

<u>Glacier Dammed Lakes and Outburst Floods in Alaska (Post and Mayo, USGS 1971) (and other sources)</u>

The Knik River is fed by the Knik Glacier, Colony Glacier, and George Glacier, as can be seen in Figure 6 below. According to Post and Mayo (1971), an interesting contribution to the Upper Cook Inlet, through the past 200 years of annual river flow, is jökulhlaup, a glacial outburst flood, or specifically, ice jam flooding [21]. An oral history of the region shares that in roughly 1899 there was a significant event that changed the topography of the region. Just before 1900, three Indian villages along the Knik River were destroyed by a great flood, which was believed to be the result of the breakout of Lake George, according to Kari and Fall (1987) [22].

No previous flood damage along the Knik River had been recorded, although the lake emptied once every 15 to 20 years according to Indians living in the area. Based on the 20-foot water level rise mentioned by Kari and Fall (1987) [22], a roughly calculated discharge estimate is 420,000 ft^3/s (12,000 m^3/s)*.

The annual flooding of Knik River was consistent between 1918 and 1963 that flood experts, such that bridge maintenance crews, and tourists reserved a week in July or August for the event, ultimately resulting in the area being designated as "Lake George," a National Natural Landmark by the National Park Service in 1967 [23]. According to recorded estimated peak discharge of 292,815 ft^3/s (8,290 m^3/s) as captured by the National Water Quality Monitoring Council [24] is assumed to have occurred with the regular flooding, correlating to 10 feet water height [21]. In 1920, there was another large jökulhlaup event, when the Knik Glacier ice dam broke and Lake George emptied with an estimated peak discharge of 400,000 ft3/s (10,000 m^3/s) *. This event resulted in the fledgling Matanuska community being abandoned due to flooding damages [25]. According to Post and Mayo (1971), from 1949 through 1961, there was a significant rise in the peak discharges [21]. USGS gage and streamflow data available provide an average value of about 261,930 ft^3/s (7,420 m^3/s) [24] is assumed to represent the regular flooding events [21]. Between 1962 and 1966, the peak discharges were lower than during the preceding decade (estimated at 165,000 ft^3/s [4,670 m^3/s] *). "The cause of these latter changes was undoubtedly due to a thinning of the ice at the glacier terminus, which in recent years has been the largest glacier-dammed lake in Alaska. It was noted in 1963 that that the lake emptied annually since 1918, at least" [21].

** These are very simple and rough estimates of the discharge based on arctic river hydrology assumptions and collected average and monthly discharge data.

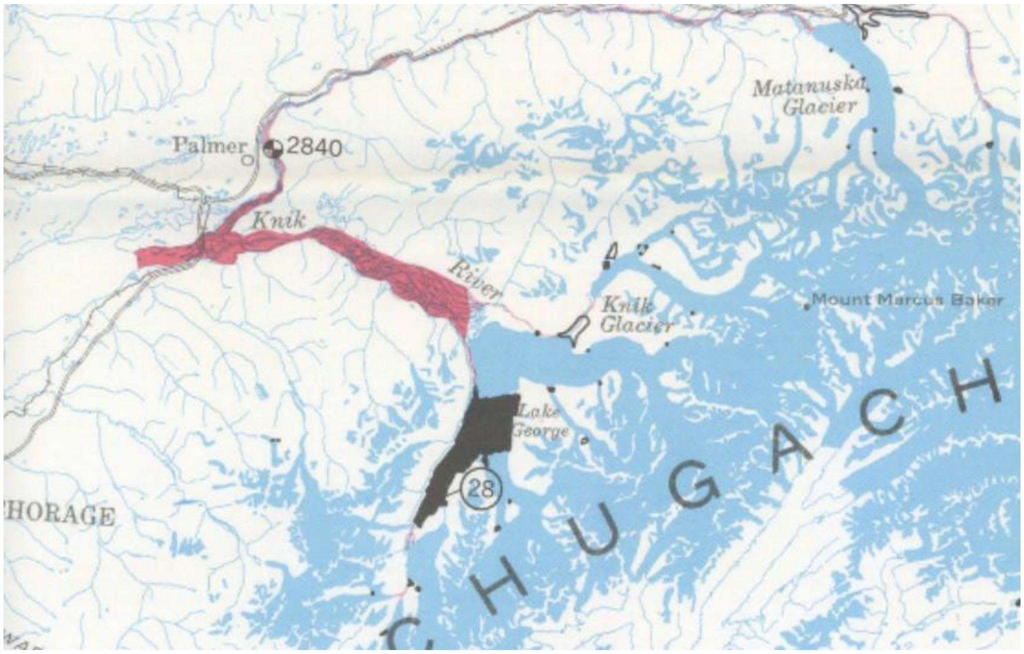


Figure 6: USGS Map of Lake George, as dammed by the Knik Glacier, from 1918 to 1962 [21].

"In 1964, there was a large earthquake in area (magnitude 7.1 [since updated to 9.0]), no significant dam related activity was reported, according to Post and Mayo (1971) [21]." This year had an estimated peak discharge volume of 236,000 ft^3/s (6,682 m^3/s) *. "In 1965, 2.4 meters (8 feet) of scour and 1.2 meters (4 feet) of fill occurred locally in the channel from July 9 to July 11, 1965 [21]." This year had an estimated peak discharge volume of 144,000 ft^3/s (4,080 m^3/s) *. Additionally, in 1966, the Knik Glacier "failed to form an ice dam and the lake has not filled. In this case, a period of regular lake dumping lapsed briefly and later ceased abruptly [21]." This year had an estimated peak discharge volume 35,900 ft^3/s (1,020 m^3/s) *. At the time of its designation in 1967, Lake George was the "largest glacier-dammed lake and one of the most consistent self-dumping lakes in North America. The lake emptied almost annually for 49 years before 1967. When the lake outlet was blocked by the Knik Glacier, the lake swelled with water until summer when the dam broke and the water dumped in a spectacular torrent into the Knik River" [23], with an estimated peak discharge volume of 32,700 ft^3/s (925 m^3/s)*, as shown in the Alaska Film Archive video of similar events [26].

In 2017, the Knik Glacier ice dam potential showed an estimated peak discharge volume 47,900 ft^3/s (1,360 m^3/s) *. Further research shows that "over the last five years … the gorge of the Knik [has gotten] wider and wider up to a point where it now is almost navigable in the summer," according to Craig Medred News, in an article entitled, "Glacier dams Knik" [25].

This information is valuable to the evaluation and review of a sediment budget in the perspective that the available data may not provide a full picture of the sediment transport in the watershed. The glaciers are a significant and not clearly connected source of both the water and sediment. The various movements, changes in annual patterns, and otherwise characteristics of these glaciers may not be clearly connected with the lower watershed dynamics. These historical points with the Knik River help to demonstrate that the rivers around us hold mysteries and keys to understanding.

2.2. Currents and Data Sources for Circulation and Tidal Flow Modeling

<u>Calibration of Tides in an Operation Forecast System for the Shelikof Straits – Cook Inlet Region of Alaska (Lanerolle and Patchen, 2012)</u>

Over the last couple decades, NOAA's Center for Ocean Observation Programs (COOPs) has collected many months of depth and current velocity data in Cook Inlet, Alaska. This information was collected to update navigational aids and to quantify the tidal energy in the region. Since 2002, approximately 50 acoustic Doppler current profiler (ADCP) assemblies have been deployed in Cook Inlet. The data goes through specific data processing from NOAA prior to being made available to the public.

The Lanerolle and Patchen [15] report relates to accurately modeling the frequency and magnitude of tides in Cook Inlet. The modeled tides were validated with measured values and those provided by the National Oceanic and Atmospheric Administration (NOAA) 2016 Cook Inlet Current Study Report from NOAA in 2009 and other Cook Inlet online current data. In 2005, during numerical evaluation and comparison of the collected data with a ROM-based circulation model, irregularities were found. It was anticipated that ADCP measurements could calibrate the model [15].

Four locations that are of interest to this thesis include three deployments (CI0501, CI0502, and CI1206) in the Forelands region of Cook Inlet, where the tidal flow is significantly constrained due to a narrowing in the waterbody, and one at the southernmost region in Cook Inlet and the Kennedy Entrance (CI0418), according to Ewald and Paternostro [27]. The tidal energy experienced at these two locations is considerably different and provides a range for review [27]. A visual representation of Cook Inlet bathymetry is provided in Figures 7 and 8 below. These deployments used an assembly approach that had been successful in other parts of the world: a mooring chain, anchor, railroad wheel (due to their compact, heavy and readily available nature), and ADCP. In certain areas of Cook Inlet that had both deeper water and more intense currents, it appears as though modifications were needed to protect the integrity of the measurements. In the deployments from 2002 till 2005, standard assemblies were used. There were three deployments across the Forelands, and CI0501 is in the center. The mooring line was 6.1 m (20 ft) and the total water depth in the area is approximately 33.2 m (109 ft). The fastest velocity was experienced on August 17, 2012 at around 300 cm/s (6.7 mph or 5.8 knots) [27].

Of the 2012 deployments at the Forelands, CI1206 was the most westerly oriented. The mooring line was 6.1 m and the total water depth in the area is ~38.2 m (125.3 ft). The fastest velocity was experienced on August 17, 2012 at around 280 cm/s (6.26 mph 5.4 knots) [15]. The deployment assemblies used in the 2012 measuring campaign utilized with two or three subs, elongated flotations in the shape of a torpedo, placed along the mooring line to provide vertical stability in the ADCP position.

In 2012, a deployment on the northwest side of the Forelands, COI1205, was lost after staying in location for 10 days [28]. The ADCP and mooring line was eventually recovered, but all the data collected during the 10 days of deployment was lost. During the deployment, the ship captain noticed that there were large sand waves, or boulder waves present on the sea floor [29]. Based on this information and the frayed morning line, it is theorized that a boulder wave migrated onto the mooring anchor and rocks stabilized the bottom-most section of the mooring line. The upper section, subs, and ADCP would have likely still been exposed to the rather large velocities and sediment laden sea water [29]. This upward shifting of the fulcrum point and removing the flexibility provided by the railroad wheel could have caused the mooring line to fray after 10 days (about 20 tidal cycles) [27], bending the cable in ways it was not designed to withstand as suggested by Danielson, et al. [30].

In a personal interview with C. Paternostro [29], he shared that this (COI1205) is where the migrating boulder waves are assumed to reside. A large gas leak in this area, likely caused by the migrating boulder waves that are part of the local lore and have yet to be well documented. For the locations near the Forelands, it is particularly intriguing to review, as that is where the fastest velocity was measured during the deployments. Considering the COI1206 buoy mooring line fraying to a breaking point in just 10 days, it is particularly of interest to better understand the dynamics present. This is interesting since nearby (slightly more to the northwest, towards

Trading Bay), sediment samples collected in about 1995 show that the sediment is predominantly sand and 2–3% silt content (ICIEMAP/EMAP Cook Inlet sampling) [9].

A fourth deployment, COI0510, was in the Kennedy Entrance to Cook Inlet in considerably deeper and calmer waters. The mooring line was 100 meters (328 ft) in length and water depth of about 150 meters (492 ft). During deeper evaluation, vertical excursions or suppression in the location of the ADCP in the water column were noticed. The lowering and lateral movement of the ADCP was caused by intense currents acting on the mooring chain.

This information is valuable to the understanding of Cook Inlet as one of the most dynamic waterbodies on the planet. The water speed and forces that occur in the Forelands area are a defining feature. This information is also important for validating models as the water speeds seen and the particle size capable of movement are not typical.

Figure 7: Map of selected NOAA ADCP deployment locations in the Cook Inlet Forelands.

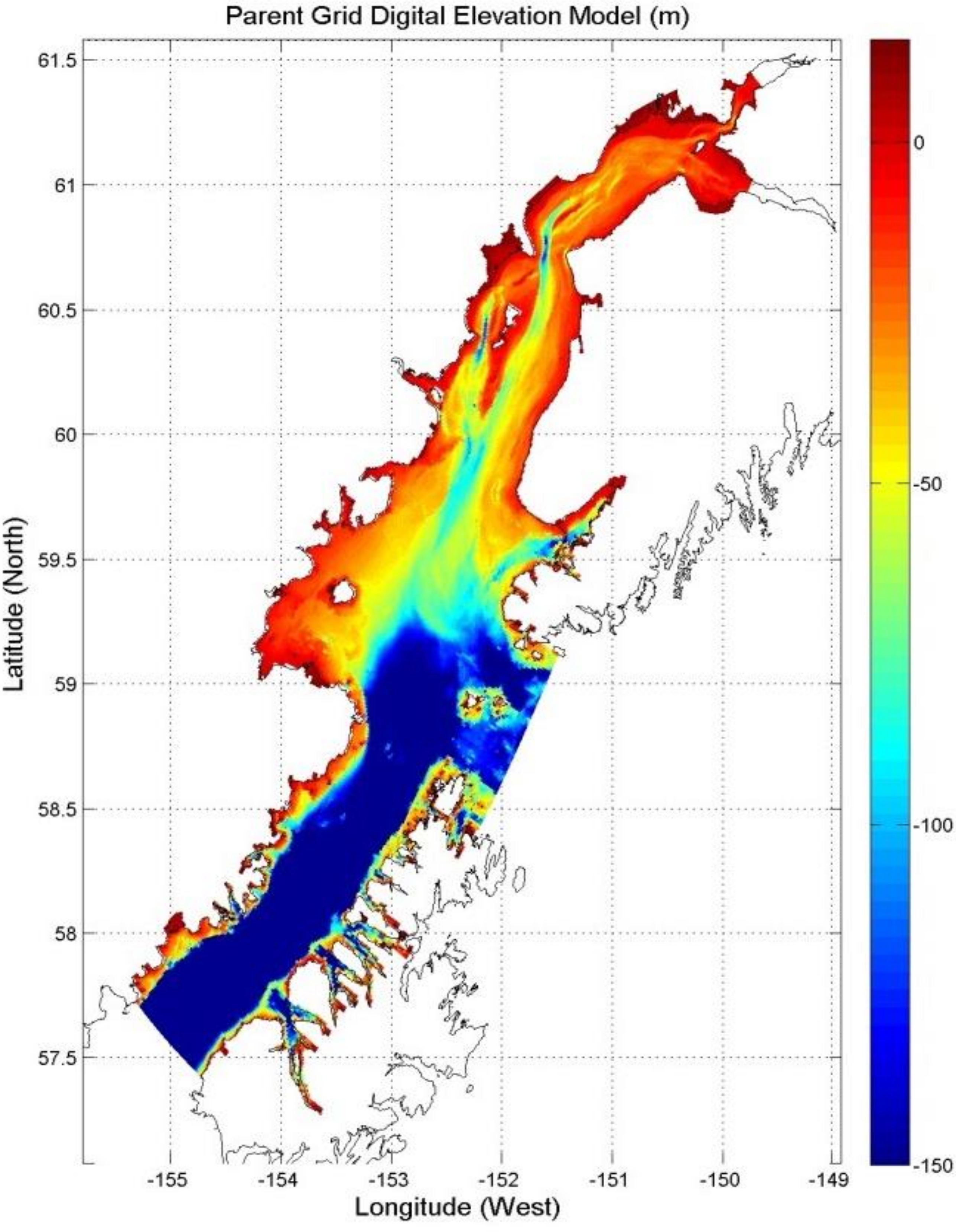


Figure 8: NOAA CO-OPS color rendering of Cook Inlet bathymetry for tidal flow modeling [15]

Water and Ice Dynamics in Cook Inlet (Johnson, 2008)

This study was completed in part to assist with spill response activities related to oil and gas leases. A model was developed based on data from 1949 to 1999 which showed detailed stratification. Initially the model did not include wind, heat flux or river discharges. These model runs show that the monthly subtidal currents stayed consistent throughout the year. Details regarding the tidal rips in terms of location and seasonality are provided, both modeled and observed. The harmonic constituents included account for approximately 75% of the tidal dynamics (M2: 3.5 m, S2: 1.0 m, N2: 0.6 m, 2N2: 0.14 m, K2: 0.27 m, K1: 0.69 m, O1: 0.39 m, Q1: 0.14 m) [14]. This report shows preliminary modeling efforts that have since been expanded and refined, including the use of bathymetry and tidal flow vectors to reasonably estimate the dynamics of Cook Inlet [14]. At the time, the author discussed an experimental particle tracking effort with LaGrangian foundations for a time period from August 15-31, 2005. Further, one of their studies suggests that tidal motion is the dominant process controlling water movement in Cook Inlet. According to Johnson, this study "also showed that particle movement was sensitive to water stratification" [14].

Depth dynamics, related to varying densities of water at depth and sediment concentrations, significantly impacted particle pathways, as shown by model comparisons of drifter simulations where the north-south wind direction was a forcing factor. The "meso-scale temporal and spatial variability of the water stratification and missing due to surface wind and heat fluctuation must be resolved to accurately simulate the dynamics" present in Cook Inlet. Further, Johnson's report suggests "that it is critical to resolve accurately the subtidal currents in Cook Inlet in order to provide the realistic water transport process in the region." [14]. This study was both inspiring (as it was the closest to a complete model available) and very informative. The efforts that Johnson and the UAF team put forth are commendable. Their conclusions are fundamental and re-enforce the research and model efforts summarized in this paper. Their drifter studies are a direct parallel for sediment and circulation at depth being sensitive to stratification.

Cook Inlet Circulation Model Calculations (Danielson, et al., 2016)

The team at the University of Alaska Fairbanks expanded and updated their work at the Institute of Marine Science School of Fisheries with this report. The Danielson, et al. [30] evaluations focus on the Gulf of Alaska, the Alaska Coastal Current, and circulation dynamics in Cook Inlet and Prince William Sound. The model uses a 1.5 km horizontal resolution and 50 layers in the calculations. Of specific focus is temperature and salinity modeling at depth, with the results showing a slight bias towards denser and cooler at depth and fresher and warmer at the surface. The study and related modeling efforts were funded to support the U.S. Bureau of Ocean Energy Management's Oil Spill Risk Analysis as part of expanded Outer Coastal Shelf oil lease sales in the region. Danielson, et al. [30] used state of the art modeling to look closer at the lower part of Cook Inlet and Shelikof Strait, with a focus on circulation and mixing. Their efforts also attempt to include the freshwater river inputs, based on USGS data, with the Copper River and Kenai River as major sources. They also include wetting and drying for the Cook Inlet and Copper River tidal flats as well as a sea ice algorithm [30]. The modeling efforts are significant update to the available approaches and show that understanding and interest in the region is evolving. Their evaluations do not include sediment, or a detailed look at the upper Cook Inlet contributing rivers and elements.

2.3. Sediment Transport and Dynamics

Fine sediments deposit on the mud flats during the high tide (upper half of the tidal range) when quiescent (calm) conditions with little movement exist. Under wavy conditions, the sediments are re-suspended and advected (or moved) away. Sea ice seasonally (fall, winter and spring) attaches to the tidal flats, freezing sediment into the bottom layer and forms bottom-fast ice. This sediment is transported away when the bottom-fast ice floats away. In winters, with frequent thawing episodes, the freeze and thaw cycle can be repeated multiple times leading to more sediment transport away from the mudflats [31].

<u>Numerical Modeling Studies Supporting Port of Anchorage Deepening and Expansion – Part IV: Numerical Sediment Transport Modeling (Hayter and Smith, 2012)</u>

This report summarizes the results of a US Corps of Engineers study with Environmental Fluid Dynamics Code (EFDC) to evaluate six (6) proposed port expansion configurations. The model used was driven by ADvanced CIRCulation (ADCIRC) -simulated tides at the Forelands, near Nikiski. The sediment transport rates were calibrated based on an averaged (2-month period) sedimentation rate of 4 cm/day and dredging records. The model was additionally calibrated with the comparison of measured and simulated tides at both the Port of Anchorage and the ADCP transact line in lower Cook Inlet. The simulated suspended sediment concentration based on a 60-day simulation is 3,000 mg/l. The model used uses a curvilinear-orthogonal grid with 24,434 horizontal grid cells, which are used to represent open water from Knik and Turnagain Arms to the Forelands at Nikiski. The size of the grid cells vary from 10m×30m (in the Port) to 400m×3,000m (at the Forelands), depending on the area of focus. Based on the assessment, dredging in the Port of Anchorage is anticipated to increase, mostly due to deepening and expanding the dredging area (Hayter and Smith) [3].

Astronomical tides were the dominant forcing mechanism with river inputs included as a secondary mechanism, and winds are neglected. Wind waves were not included due to the relatively small increase in bed-shear stress. Bottom friction and Coriolis acceleration were accounted for and the model was run in depth-average mode. The sediment class sizes and related settling velocities from Upper Cook Inlet (Knik Arm) were as shown in Table I below:

Table I: Port of Anchorage Grain Sizes and Settling Velocities

Grain Size	Grain Type	Settling Velocity
34 μm –	silt (assumed to be cohesive)	not mentioned
250 μm	fine sand	2.67 cm/s
1000 μm	medium sand	11.1 cm/s
8520 μm	medium gravel	41.2 cm/s

Data gaps acknowledged in the report include very limited suspended sediment concentration measured data in upper Cook Inlet (Knik Arm region) and unknown mudflat and bank erosion rates. These data gaps may have contributed to a high shear stress value that was used in the model. The model was able to accurately simulate gyre activity between Cairn Point and Point Woronzof [3]. This information is valuable to the development of a sediment model and understanding of the upper Cook Inlet sediment dynamics. On one hand, the settling velocities, sizes, and dredging study show that the delta dynamics of the Knik and Susitna Rivers are still not completely understood. In addition, the acknowledgement of missing erosion rates points to the use of other studies to support a sediment budget for the region.

Sediment Resuspension in Boston Harbor (Ravens, 1997) and Flume Measurements of Sediment Erodibility in Boston Harbor, (Ravens and Gschwend, 1999)

Ravens and Gschwend [32] utilized a sedflume to measure deposition and erosion rates with storm events in Quincy Bay of Boston Harbor, Massachusetts. In situ measurements of sediment erodibility were obtained in defined bottom shear stress environments with the use of a portable, straight flume. The design of the flume prevented erosion of the sediment bed in the boundary layer region. The experiments looked to see whether algal mats had an impact on the erosion rates. In the absence of algal mats, there was "uniform erodibility, with a critical shear stress τ_c of 0.10 ± 0.04 Pa and an erosion rate constant M of 3.2 ± 0.2 × 10-3 kg/m^2 s^1 Pa^1." Erodibility lessened by 50–80%, when the sediment was covered by a benthic diatom mat [32], [33]. This information is valuable to the development of a sediment model as the critical shear stress value is a reasonable approximation and was used as a model parameter. No additional research was done to assess whether algal mats are present here in Cook Inlet.

Erosion, Transport and Deposition of Fine-Grained Marine Sediments (McCave 1984)

McCave points out that the fluid stress required to remove particles cannot be predicted due to the complexity of the physiochemical and biochemical bonding forces, the amount of compaction and biological components found in cohesive sediments. He also notes that as the sand content increases, the critical erosion shear stress increases, which leads to increased compaction rates. These observations are guiding thoughts as this thesis develops. McCave's paper summarizes and clarifies technical details regarding fine-grained sediment dynamics. Due to the physiochemical and biochemical bonding forces and degree of compaction and biological components found in cohesive sediments, the fluid stress required to remove particles cannot be predicted. This may be the dominant form of sediment flux. In the data that McCave reviewed, temperature dependent erosion rates did not include assessments close to freezing, and he theorizes that increased erosion rates at cold temperatures measured in laboratories may be attributed to biota reductions as diatom populations certainly play a role. An additional conclusion made is that increased salinity is related to decreased yield activation energies and flow over illite particles [34]. This information is valuable to the to the development of this paper for mud flat sediment understanding.

An In-situ Erosion Rate for a Fine-grained Marine Sediment (Lavelle, et al. 1984)

This work builds on previous efforts regarding the erosional response of a fine-grained sediment to bottom stress and provides details regarding height dependent diffusivity. He notes that diffusivity is dependent on bottom fluid stress. Their paper builds on previous efforts and attempts to provide a targeted model that accurately predicts erosion rates. The paper shares inferences about the erosional response of a fine-grained sediment to bottom stress. The discussion is based on near-bottom current and particulate concentration data and a theoretical model of sediment resuspension. A comparison of in situ erosion rates with previous estimated laboratory rates is made for some freshwater sediments. In addition, observations made 5 m from the bottom in the main basin of Puget Sound, Washington, show that currents with speeds exceeding 40 cm/s cause an increase in concentration as much as six-fold from a background level of 1 mg/l The analysis also points to sediment resuspension of material with relatively large settling velocity (w_s=0.1 cm/s) taking place against a background of much finer particles and a depth of sediment reworking of approximately 0.3 mm under typical strong flow conditions. In light of these observations, Lavelle et al., provides details regarding height dependent diffusivity, which depends on bottom fluid stress [35]. This information is valuable to the development of this paper as these settling velocities were used as a baseline.

Sediment Quality in Depositional Areas of Shelikof Strait and Outermost Cook Inlet (Boehm, 2000), Cook Inlet & Shelikof Strait Sediment Study (MMS, 1998) and Cook Inlet Sediment Study (MMS, 2001)

These studies include more sediment samples in known depositional environments and associated evaluations to determine depositional rates (related to wave and current dynamics). In addition, the research efforts were able to point out the depositional rates by use of known contaminants, their usage times (some had since been banned), and to show a comparative net impact of various industrial activities in the region. An interesting discovery noted in this study is that roughly 90% of pollutants discharged by local sources were flushed out of Cook Inlet within ten months [36]. This information is valuable as these depositional details were used as a baseline.

Flocculation and the Physical Properties of Flocs (Lick and Huang, 1993)

Lick and Huang were able to determine through the use of a sedflume that the length of time that sediment has to deposit is directly related to the strength of the sediment. Further, the modeling approach embedded in the software is based in part on his work regarding fine-grained sediment flocculation and settling [37]. This information is valuable to the to the development of this paper as the initial assessment was looking at the sea floor boundaries of the sediment for mud flats. The saline and clay interactions on mudflats could be assess for their depositional rates.

Chapter 3: Presentation of Methodology for Reaching Thesis Goals

Initial research was based on gaining better understanding of the flow and circulation patterns in Upper Cook Inlet in relation to the oil and gas platforms and their wastewater discharge permits. At the time, exploration drilling was the topic of concern, and specifically USGS stream gage data was obtained to understand how much the total amount of oil and gas drill cuttings compared to an annual amount of glacial silt from the rivers.

The first, and therefore very influential, information found was the USGS Water Quality in the Cook Inlet Basin report, which provided a summary of annual inputs from main rivers into the region, totaling about 40 million metric tons of sediment a year (Glass, et al.) [7].

The next step was to learn of the stratification dynamics that are part of Cook Inlet due to the fresh water inputs from the rivers and the saline inputs from the Gulf of Alaska (Okkonen, et al.) [1]; (Johnson) [14]. There are several reasons why this is of interest, most of them related to the mixing dynamics due to density, velocity, and diffusion. Specific details related to density, pressure, and temperature at depth were collected as part of previous discharge permits, and these data points provided a perspective into the varying layers of water and are directly related to the predictable diffusivity of an anticipated discharge.

The data set consists of several days in August, over two summers, and presented an opportunity to create a model that could run year-round simulations of water density. Ulmgren had developed a model to better understand the sediment transport implications of potential hydrokinetic energy generation in Cook Inlet [38]. This model was built with the EFDC and Delft3D modeling programs, and some time was spent building on this model to incorporate water quality data.

The USGS river data would be a source for reasonable model inputs. A more detailed review of the data set considered the sources of data, potential comparability of rivers, and a statistical assessment of the sources of sediment and flow into Cook Inlet. Also gathered were boundary conditions and tidal forcing details that would help generate a somewhat realistic model. These elements are discussed in more detail below.

3.1. River and Sediment Data Sources and Selection

The initial assessment of the Cook Inlet river stream gage data included a review of 30 years of studies, 473 sampling stations, and approximately 3 million data points (National Water

Quality Monitoring Council) [24]. Specifically, targeted were data collected between 1998 and 2015 from USGS studies that included sediment reported in tons per day. The assumption was that by taking such a wide view of the rivers that are part of Cook Inlet, the assessment could capture the main sources of flow and sediment.

Once the data were collected, some initial sorting and cleaning was conducted to allow for a simple comparison or analysis of variance (or ANOVA) within the data sets†. It appears that something changed in the data collection techniques, and that data has improved in consistency for the parameters of interest in the recent past. Sufficient data (based on similar data collection technique) for analysis was available from 2000 to 2014. Figure 9 below shows a summary of those data points.

To conduct this analysis, an ANOVA statistical comparison was set up to see whether location, time or flow are more significant in relation to the amount of sediment in the river‡. A multiple regression analysis approach was selected, with the null hypothesis stated as follows:

Equation 1: $$H_o: \beta_i=0,\ H_a: \beta_i \neq 0$$

where H_o is the null hypothesis and H_a is the alternative hypothesis. β_i is the annual average of the sediment concentration for each river. Otherwise stated as: the hypothesis is that the variance in these data sets is zero. To simplify the comparison, it was assumed that the data is without error (inaccurate, but practical), and that the data is normally distributed. (Scripts and comparison structures provided in Appendix A.) The results of this analysis are discussed below in more detail. They led to an initial conclusion that the sediment flow into Cook Inlet is increasing in recent years. Which fit well with the other assessments within the region in relation to glacial melt (O'Neel) [17] and dredging volumes at the Port of Anchorage (Hayter and Smith) [3].

Then the six main rivers that provided the largest flow and sediment contributions (noted in Table II below) were looked at in greater detail to better assess whether the increase was a result of specific data or an actual physical trend that exists for all the Cook Inlet Rivers. This assessment was done by searching for available data within the USGS data sets specifically for

† There was an error in 2008 [67] that is captured on Figure 9 was taken out for the statistical evaluation by the software program R as an outlier.
‡ The interdependence of the data makes an ANOVA assessment less than ideal, so the interpretation is open to additional statistical investigation. It was simply the starting point for this study.

each river and looking at many more years (1958 to 2019) of stream flow to find trends. Other sources show that significant variation in the amount of sediment in the rivers has occurred in the past several hundred years in relation to Lake George emptying [22] and as shown in Alaska Video Film Archives [21]. The analysis is a matter of digging for data and collecting it in comparable formats. As shown in Figure 9, there is a large variation in the amount of sediment for Cook Inlet rivers. There is a significantly large value, which additional research showed was attributed to the Yentna River.

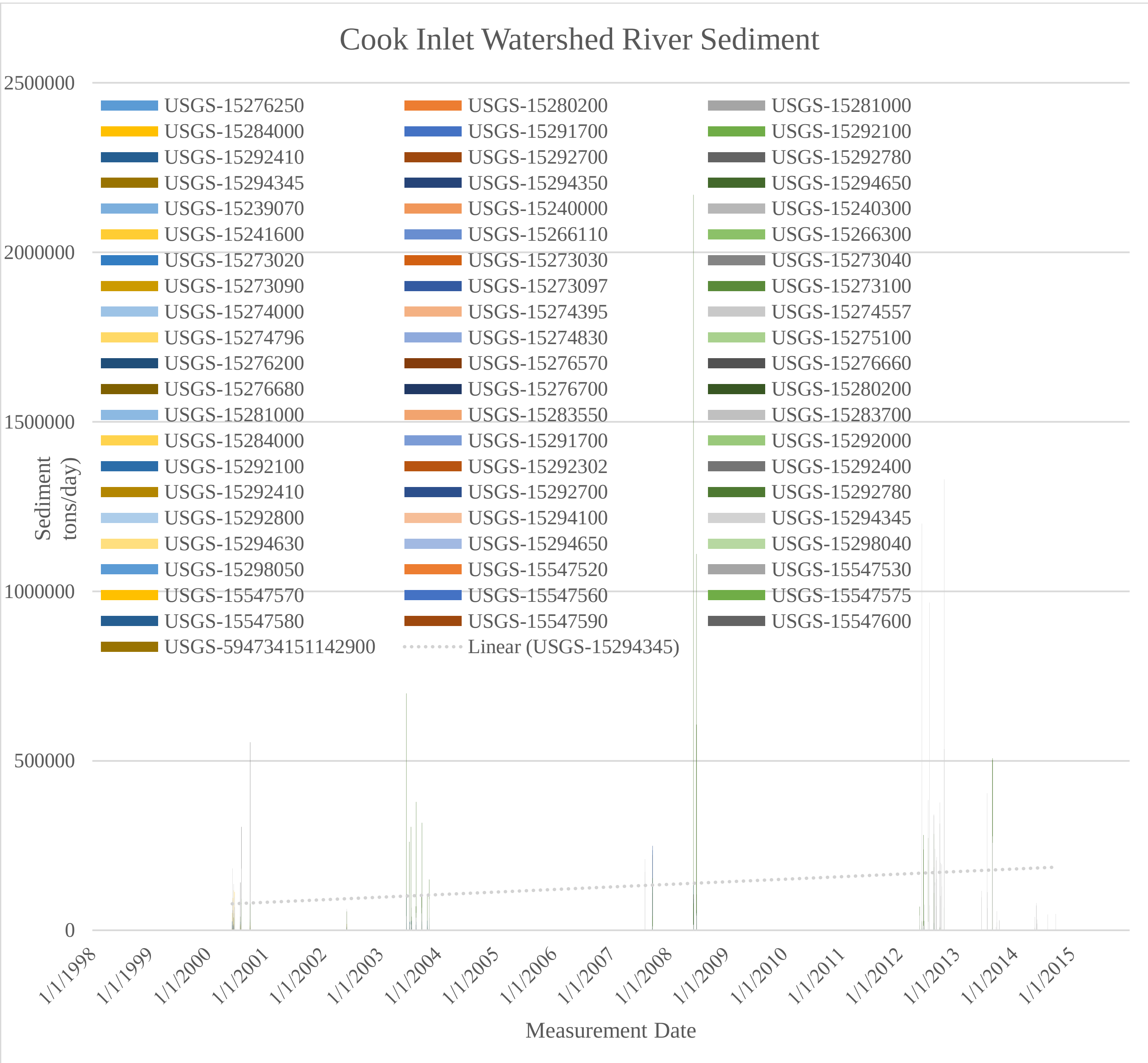


Figure 9: Individual river flow data plotted, showing available sediment in tons per year by river and date. This table has been reproduced from previous analysis efforts to show date sources.

Table II: Summary of River Data Reviewed

Monitoring Location Identifier	**Monitoring Location Name**
USGS-15281000	Knik River at Palmer
USGS-15284000	Matanuska River at Palmer
USGS-15292100	Susitna River near Talkeetna
USGS-15292400	Chulitna River near Talkeetna
USGS-15292780	Susitna River at Sunshine
USGS-15294345	Yentna River near Susitna Station
USGS-15294350	Yentna River near Susitna Station
USGS 15290000	Little Susitna River near Palmer

3.2. Sediment Budget

The Sediment Budget is effectively a conservation of mass view of a region. The amount of sediment can be quantified for a region based on known sources and sinks. Examples of sources include glacial flour in rivers, erosion from flooding or tidal influences. Examples of sinks are depositional areas such as river deltas and tidal flats, or deeper water in the ocean according to the Longshore Transport chapter in the US Army Corps of Engineers *Coastal Engineering Manual* [39]. The assessment assumes that the amounts are somewhat static in the moment, where the amount of sediment that enters the regional area is also the amount that is deposited or leaves the regional area. The initial efforts to understand the amount of sediment that enters Cook Inlet from rivers provides a significant portion of the sediment budget.

Additional evaluation of bluff erosion as a source and quantification of those amounts is also part of understanding the regional sediment budget. Once the sediment enters the regional area, it may not stay suspended the whole time. Depending on the path taken, it may temporarily be deposited on a tidal flat, and resuspended with the next large tide movement.

Further understanding of sediment deposition rates in portions of Cook Inlet also help fill in the details for a sediment budget. Some information can be collected for the dredging patterns at the Port of Anchorage. Data collected in other studies provides settling velocities and particle size distribution details that can be used to create assumptions for depositional areas. This information is also valuable to harbor and port engineers who are trying to minimize dredging costs.

3.3. Computer Model Development

Globally, there is interest in better understanding of regional dynamics in macro-tidal environments [40]. Models have been developed to understand morphology over time (50 to 300 years), which is beneficial for model validation and for application to areas where decades of observation data may not be available or documented. Forecast (prediction) models for tidal flats are often validated with field-data, leading to a more refined application of existing empirical equations [40].

As interest in coastal regions and changing coastlines increases, the ability to understand waves, erosion, and coastal processes has been evolving [40]. Each region of the world appears to be looking at both understanding how the existing coastal areas evolved (hindcasting) and seeking insight as to what changes may be coming (forecasting or predicting), like sea level rise, bluff erosion, and tideland morphology. Much of the foundational equations used in models have evolved from either laboratory or small-scale field studies and rely on some empirical analysis [41]. Since most of the work is exposed to micro- and mesa-tidal scales, these empirical calculations approximate these environments reasonably well. In macro-tidal regions with large tidal flats and Arctic coastal dynamics, the empirical or standard equations may be less applicable [17].

The Delft3D modeling program (version 4.2) allows for the input of many parameters to drive the model. Delft3D-FLOW is a numerical model based on the finite differences developed at the Delft Technical University in The Netherlands. The model relies on a system of unsteady shallow-water equations, consisting of the continuity equation (excluding evaporation and precipitation), horizontal momentum equations (excluding the influence of density differences) and a transport equation. The user can select to solve the shallow water equations on a Cartesian rectangular, orthogonal curvilinear or spherical grid system. The unsteady shallow water equations are solved by an Alternating Direction Implicit (ADI) method, which consistently estimates all parameters at each half timestep. Delft3D-FLOW allows three options (i.e., Cyclic, Waqua and Flood) for the spatial discretization of the horizontal advection term [40].

The basis of this thesis is to update and validate a Delft3D model to predict water quality and sediment transport within Cook Inlet. Due to the geographical location of infrastructure and related logistics, most of the sampling has been done in upper Cook Inlet. As part of the analysis, freshwater inputs along with glacial sediment were analyzed, as well as with the seasonal deposition and erosional processes that occur along the coast and mud flats. Much of the data is existing, published material, while some unpublished data was also utilized.

The intent of this project is to build on efforts undertaken in previous years. The model is be based on work done by Ulmgren at UAA, incorporating data that have been collected through many decades of research and diligent work in the region, including results shared in studies done by the USGS, Mineral Management Service/Bureau of Oceanic and Environmental Management (MMS/BOEM), NOAA, UAA and University of Alaska, Fairbanks (UAF), as well as others. Specifically, this current effort sought to include water conductivity, depth and temperature (CDT) details and water velocity from CIRCAC [8] [9] [11] and NOAA studies [15]; Sediment details from the watershed rivers, as captured in the USGS studies, annual data, and summarized above [42] [24]. Drogue results from the CIRCAC sampling efforts were entered as observations.

The ocean flow up into Cook Inlet is driven by the Alaska Coastal Current and includes salinity, temperature, and sediment load parameters as well. These inputs were added to the existing model via data points and boundary conditions, which are summarized in Table III below. The tides are forced at the Straits with open boundaries. All other data is focused in the region from mouth of the Susitna and Knik rivers to the Forelands constriction. More refined mesh was added to the base grid in the forelands and Port of Anchorage/Susitna River mouth areas to enable more reasonable results and to allow for the model to attempt to complete calculations.

Since most of the data available to build the model initially came from the CIRCAC reports, the model time period was based on the sampling dates in August, 2008. Only one term for tidal forcing was used, although it appears that the use of seven terms may be considerably more useful, as Danielson, et al., were able to do [30]. Ultimately these values were not able to be used as intended.

Table III: Boundary Conditions for Delft3D Model

Initial Water Quality and Tide Conditions				
Ref date: 8/18/2008	(W) Forelands (N)		POA	Shelikof
Grid co-ord (x, y)	569782.418, 6732467.706	588055.264, 6728638.813		
NOAA station ID	9455869		945592	9456717, NOAA16606
Grid co-ord (M, N)	41, 82	151, 95	86, 362	1,1 & 187,1
S2				
Amplitude (m)	7.74		9.45	4.43
High tide time	6:45 AM	5:33 AM	8:45 AM	3:57 AM
Latitude				59.660514
Longitude				-177.678587
Salinity (g/kg)	22.3	23.3		31.5
Temperature (C)	13.1	12.6	13.611	5
Phase (deg)	25		72	295
NOAA Tides & Currents Station ID		TWC1989		

Additional details from the Port of Anchorage dredging efforts [43] and evaluations and Knik Arm Crossing [44] evaluations were used to generate reasonable values for the model. For the Delft3D modeling options, a critical shear stress of 0.1 Pa for marine silts and clays was assumed, which is a value that is quite common [32]. These details and values are summarized in Table 4 below. The variation of sediment size and density is based on the cited sources. Some interpolation was used to create reasonable inputs for the model, as the reported values were variations of the accepted modeling constituents.

The process followed was to study the mechanisms at work in terms of sediment transport through coursework and experiments, learn and update the Delft3D model, and to analyze available data for model validation and evaluation.

The initial steps include a comprehensive review of the existing modeling software programs available and of models of the region. The focus of the evaluation was how to include the additional water quality data that is currently available. In this effort, only the Delft3D Flow module was utilized. A Deflt3D Wave module to could be developed to match. The grid and bathymetry files used came directly from Ulmgren's project. The overall flow included the sources of freshwater into the inlet as open boundary conditions at each river, predominantly from glaciers and streams (summarized Figure 14 below). These freshwater flows have specific temperature, density, and sediment loads that were considered part of the model. The base model mesh covers Cook Inlet from the mouth of the Susitna and Knik rivers to Shelikof Straits.

Table IV: Sediment details for Delft3D model

Initial Sediment Conditions												
Forelands					POA	% type						
TSS (mg/l)	TSS (kg/m3)				TSS (g/l)	gravel	coarse sand	medium sand	fine sand	very fine sand	silt	clay
67600	67.6			E20%		0	0	0	0	1.15	64.18	35
33750	33.75			E60%		0	0	0.07	3.61	6.23	67.55	23
77500	77.5			E1.5B		0	0	0.87	4.82	3.91	64.47	26
59750	59.75			ENB		0	0	2.98	9.99	3.56	58.26	25
54800	54.8			C20%		0	0	0.19	0.47	2.02	59.98	37
57950	57.95			C60%		0	0	0	0.39	1.12	63.66	35
55050	55.05			C80%		0	0	1.58	7.2	14.6	56.09	21
67500	67.5			C1.5B		0	0	0.74	1.52	3.78	65.64	28
63050	63.05			CNB		0	0.37	14.74	17.4	10.12	40.69	17
Avg	59.6611			CBG		0	1.3	82.95	6.05	1.99	6.86	0.9
sum %	93.83	kg/m3		P20%		0	0	0	0.22	0.96	64.21	35
silt %	64.05	38.21294		P60%		0	0	0	0.09	3.06	67.33	30
clay %	29.78	17.76708		P1.5B		0	0	0	0.09	3.01	67.37	30
sand %	6.17	3.681091		PNB		0	0	0	0.04	3.82	66.89	29
				PBG		0	0	0.53	3.95	20.18	59.00	16
(AKCI08-15, -16, -31: data source)				Average*	1.537	0	0	0.345	1.84	3.984	64.05	30
CIRCAC 2008 data [9]				north	1.676							
				south	1.397		KABATA 2007 Kinnetic laboratories report [45]					
				*(excluding NB&BG)			POA Dredging Reports [43]					
Shelikof:	0.005	silt (kg/m3)										
	0.005	clay (kg/m3)										

Chapter 4: Analysis and Results

4.1. Discussion of River Sediment Analysis Results

Further analysis was conducted to determine if the increase was due only to time or if location (i.e.: river) was more significant. This led to the realization that the significant increase in sediment was related to the additional river data points that are only available for a few years (see Figure 8). The Yentna River contains significant sediment, but there are not sufficient data points to establish a trend (see Figures 9 and 10). The results of the ANOVA testing show that sediment flow in rivers in dependent on location, year, and flow rate, and that location is the most significant. Specifically, the most significant locations for river flow sediment are the Susitna, Chuitna, and Yentna, all near Talkeetna, AK.

The year does have significance on the sediment rate, but flow rates have more significant impact. This could relate to the increase in glacial melt to show that the rivers are indeed carrying more sediment. Appears that data set can further simplified to provide more digestible results. For example, temperature may account for sediment load variation, but is not addressed in this data set. Additional evaluations to collect the missing data sets from the specific rivers are needed and have been attempted and are discussed below. As shown in Figure 8, the initial data assessed showed that there was more sediment in tons (short) per day recorded in recent years (2012 to 2013) than in 1998.

The result of the ANOVA approach was to reject the null hypothesis of the initial analysis in all evaluations, which translates to the sediment and flow variance values are not constant, so it is possible that they are increasing.

By looking that the last several decades of river flow data (see Figure 9), it appears that there is a consistent trend in the flow increasing among all rivers. The Matanuska River is moderately steady, while the Chulitna, Susitna, and the Knik show increases.

Comparatively, it looks like the sediment load is decreasing. There is sufficient data for the Matanuska and Knik Rivers to show trends, and both of these show decreases over the last several decades (see Figure 10). There are very few data points for the Yentna, but what is available shows that this river carries both much more water and more sediment than any of the other rivers discussed in the Cook Inlet Watershed.

The available annual data (in some cases, aggregated individually and in others aggregated by USGS), shows that the stream flow and sediment load have been fairly constant, as by the reported measurements.

The Chulitna, Knik, Matanuska, and Little Susitna rivers have data available from 1958 to recently, which provides a helpful stretch of data to review. Due to the annual variability, some can be associated with known events. Both the Chulitna and the Knik rivers show a trend of increasing measured flow over the past 60 years, with a greater increase in the Knik River. Sediment data for the Chulitna is not available, and the Knik sediment loading over the same period shows a decreasing trend. Conversely, the Matanuska River shows fairly constant flow during this same period, and a fairly constant sediment load trend. Additional river flow data is available for the Susitna River station in Sunshine, Alaska staring in the 1980s. The available data show that there is some significant variation and an overall increase in river flow. The short duration of data for the Susitna River at Talkeetna mirrors the flow spikes shown at the Sunshine station. Very little data available for the Yentna River, and they show an order of magnitude change in both flow and sediment content. This has been confirmed with river guides [46] and oral histories [22]. Sufficient data is not available for trend analysis. The available sediment data were used with a rolling average of eight years to fill in missing years when enough data were available to use to provide calculated values. The data set is provided in Appendix B.

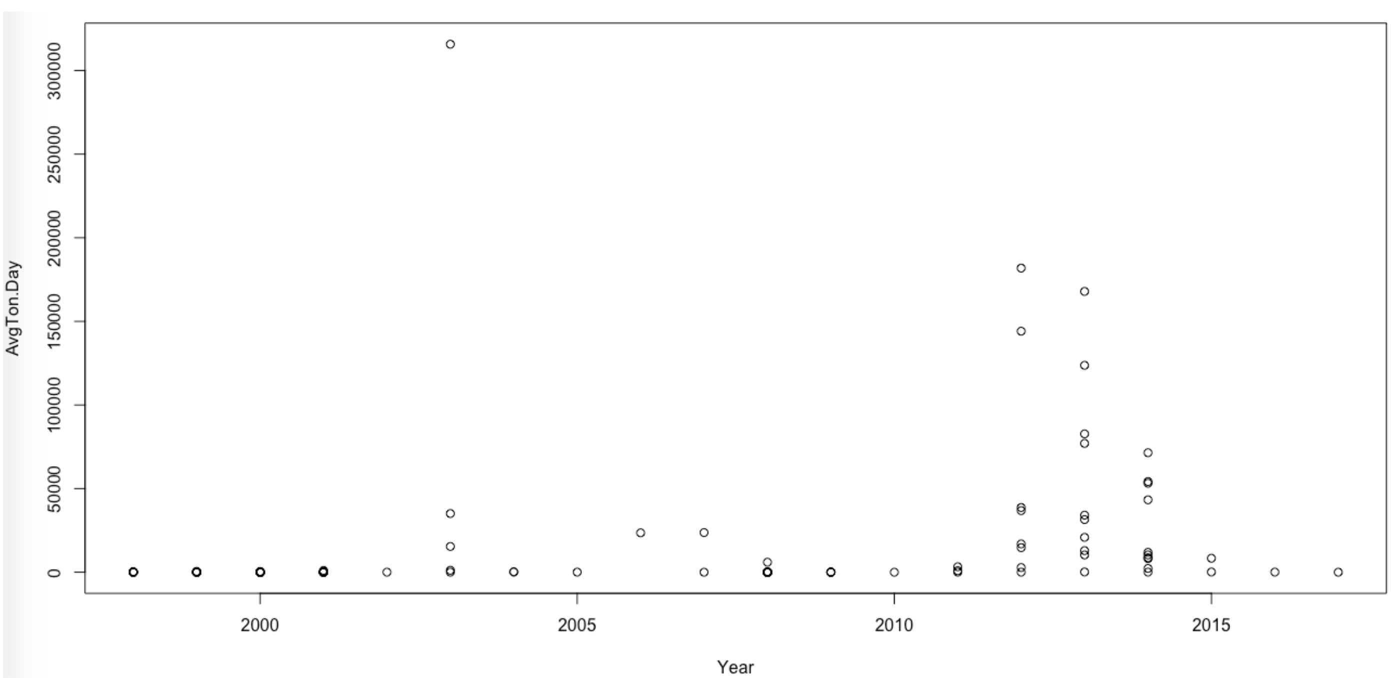


Figure 10: Initial data analysis of USGS river gage and sediment measurements, shown in average tons per day sediment from 1995-2018. With the highest amount of near 200,000 tons per day in 2012.

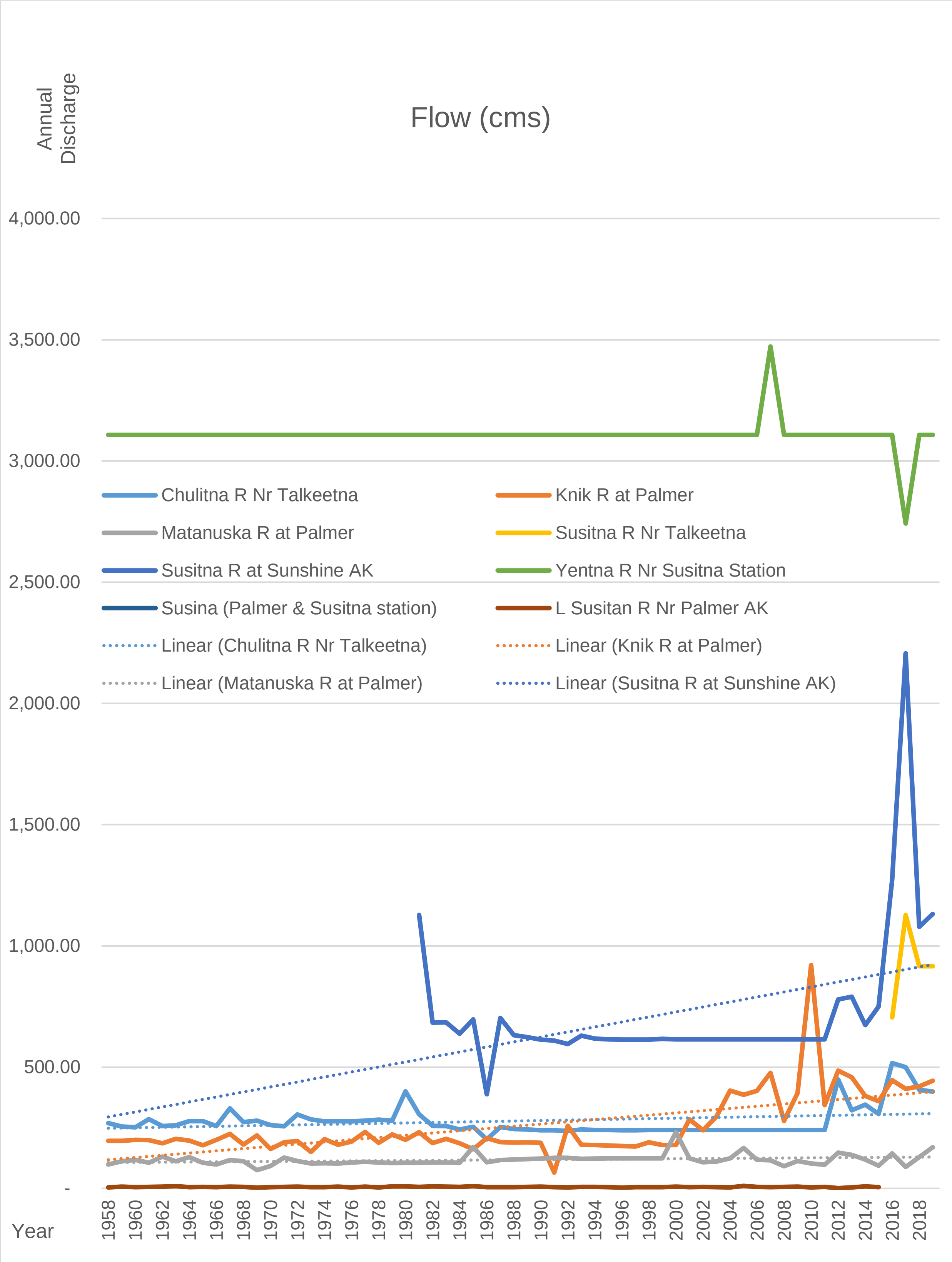


Figure 11: Select river annual discharges, in cubic meters per second versus year from 1958 to 2018. The Yentna River (in green) has a much greater discharge than others.

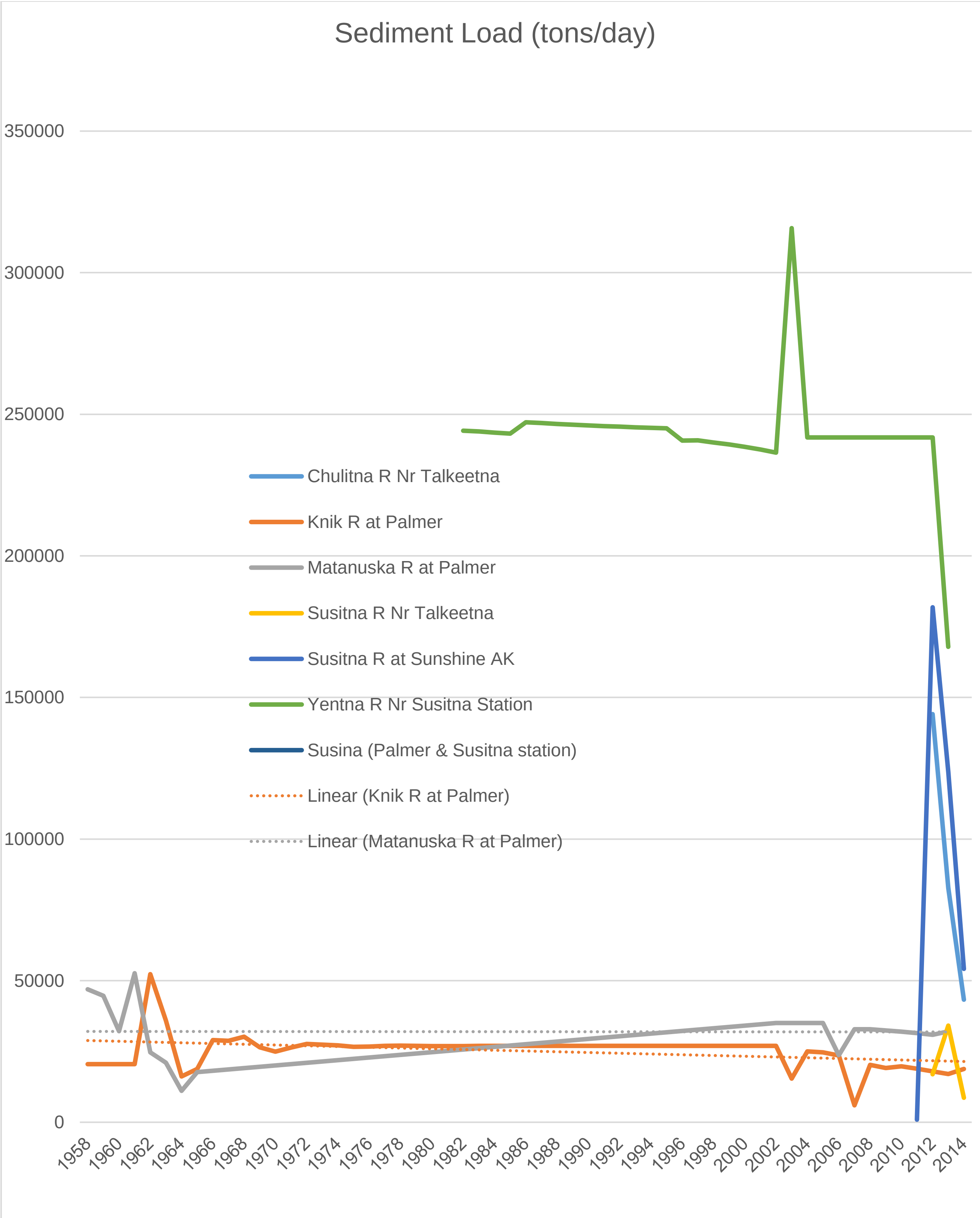


Figure 12: Suspended sediment from select rivers, in tons per day versus time, from 1958 to 2018. The Yentna River (in green) has a much greater sediment load than others.

Another way to look at the available river data is to explore rating curve dynamics. The plot shown in Figure 13 below includes potential outliers that may be associated with large storm events, and therefore may provide some insight into the behavior of the Knik River and sediments. Julien [41] explains that the sediment rating curves provide insight into the supply limitations of a given river. The rate of discharge varies with the river flow, as well as the sediment concentration [47]. The river flow gauges generally capture summer flows. Spring and fall flow increase and rain and snowmelt may be included but may also have more errors in the data and therefore not included in the calculated average values provided by USGS.

Ice floes are not well quantified in the river flow data that were reviewed. As the river discharge increases, the amount of sediment and the size of the sediment grains are also increasing, with an inverse true during flow decreases, as suggested by McLaren and Bowles [48], and Julien [47].

The Knik River sediment rating curve in particular shows that at low flow rates, the concentration of sediment is higher, and that when there are very high flow rates, the concentration of sediment is actually considerably lower. In the case of the Knik River, this makes sense since the river is a muddy, braided river that carries glacial silt and does have a limited supply of sediment. Even when there is a large event, the river path does not pass through many additional sediment sources and is not one that could provide significantly more sediment through bank erosion.

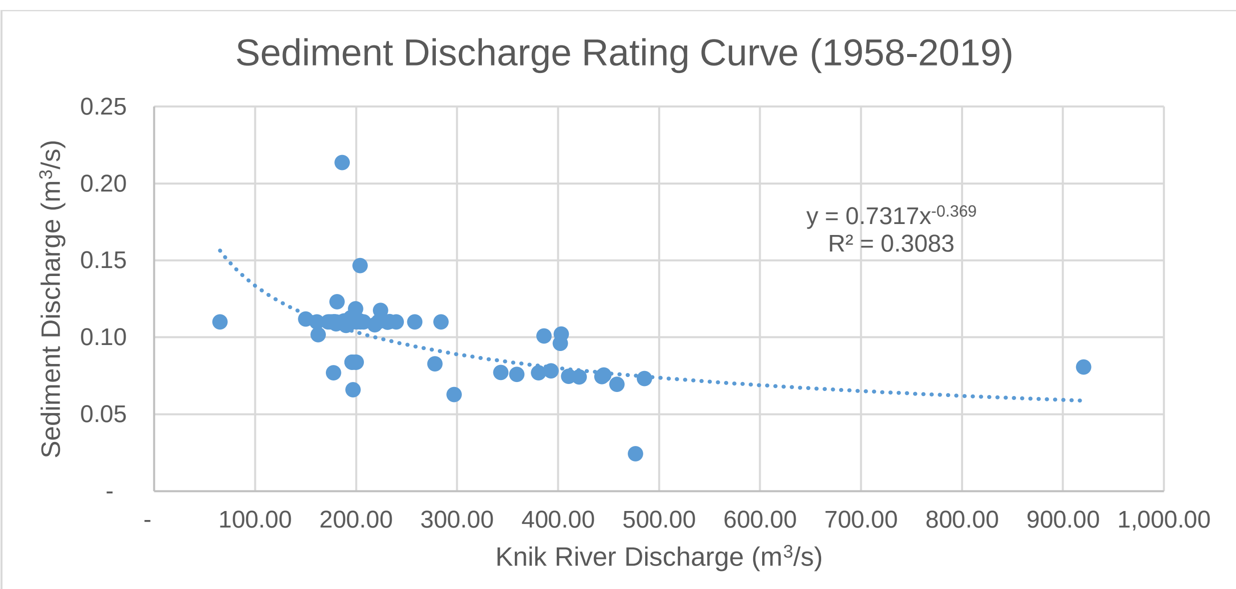


Figure 13: Sediment rating curve of the Knik River discharge, including potential outlier events between 1958 and 2019, in cubic meters per second.

4.2. Sediment Budget Results

The mass balance approach to the Cook Inlet watershed required a detailed review of the sources of sediment. This was accomplished by reviewing the last several decades of available river data, as discussed in other sections of this thesis. In addition to the sources of sediment, the actions and dynamic nature of the sediment became part of the analysis. Some regions serve as a temporary or permanent depositional site. In addition, other sources of sediment feed into the Cook Inlet aside from rivers, such as from the considerable number of coastal bluffs in the region, which have documented erosion.

The visualization of the flow of sediment from the glacier source through the rivers and resuspension areas to deposition was accomplished with a Sankey flow diagram (SankeyMatic) [49], shown below in Figure 15. The width of the line is proportional to the amount of sediment, so it is a visualization of the elements in the Cook Inlet sediment system, as defined by this budget. The boundaries are based on the Cook Inlet watershed, as discussed above. The glacial headwaters and contributing glaciers to rivers were captured via maps and collaborative data collection enabled by USGS, Google Earth images [50], and the World Glacier Monitoring Services phone application, based in the University of Zurich [51]. The inputs and values for the rivers are calculated based on the data reviewed. An average value is used for the visualization. The amounts attributed to the glaciers are estimates, based on the available data and guesses§. The glaciers are included for completeness of the system boundaries and to show a balanced mass flow. It is possible that less sediment makes the full trip from glacier to Shelikof Strait.

There have been several studies that attempt to document and calculate the rate of erosion of the coastline, as it is of considerable concern in the Upper Cook Inlet, with details available for the bluffs at Point Woronzof, Point McKenzie, and further south along the Kenai Peninsula.

Specifically, there is some definitive information available on the degrees to which the bluffs in upper Cook Inlet are eroding. Based on Geinko's work, the erosion rate is estimated to be between 40-3,000 cubic meters per day at Point Woronozof [52], (Julien) [41], (Brum) [53], (Ravens) [54]. A similar value could be assumed for the other areas. This amount translates to 100-8,400 tons per day** with an assumed density of 2,531.05 kg/m3. The density is calculated

§ The calculated values for resuspension areas and deposition are very rough and can be improved upon.
** This could further be extrapolated throughout known erosional coastal areas to get a more accurate assessment of the amount of sediment introduced into the region by coastal erosion. In this effort, rough estimates were used instead of carefully calculated values.

based on the sediment concentrations by size provided in the US Corps of Engineers and Knik Crossing reports: HDR Alaska, Inc; URS Corporation, Entrix Inc., “Knik Arm Crossing: Hydrology and Hydraulic Environment of Knik Arm” [44]; Kinnetic Laboratories, Inc. [45]; US Army Corps of Engineers, “Environmental Assessment and Finding of No Significant Impact: Anchorage Harbor Dredging & Disposal, Anchorage Alaska,” [55].

There are documented dredging activities that occur annually at the mouth of the Knik River as it is home to the Port of Anchorage, also known as the Port of Alaska. Significant amounts of cargo for the state travel through the port, and The Port of Anchorage has been dredging for several decades to maintain barge draft access [55], (Hayter and Smith) [3]; (Bryan et al.) [56]; (McAlpin, et al.) [57]. There was an initiative a few years ago to build a bridge across the Knik River, and the Knik Arm Bridge and Toll Authority (KABATA) studies and reports [45] showed several interesting observations for the mouth of the Knik River. These include that the suspended sediment concentrations are higher in the summer months, with some correlation to salinity detected [44]. The annual amounts moved (converted from cubic yards per year to tons per day) is shown in Figure 14 below. There is a significant increase in 2004 related to port expansion efforts, and a slight increasing trend otherwise.

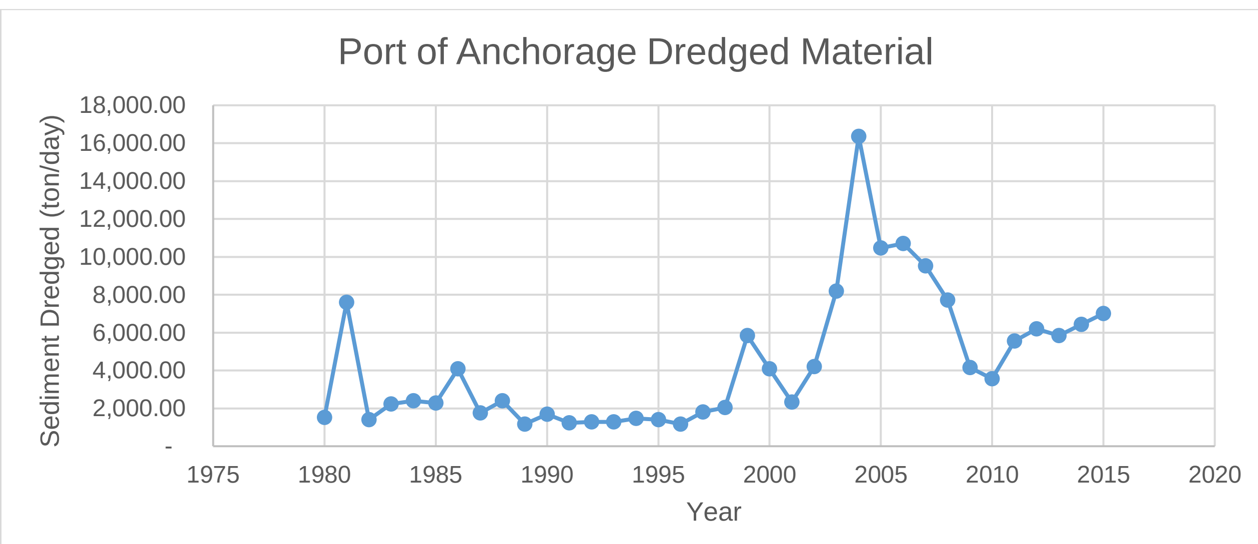


Figure 14: Summary of Port of Anchorage annual dredging volumes (Eisses, 2016) [58].[††].

When the dredging values in Figure 14 are compared with the Knik River sediment content trend line from Figure 12, there does not appear to be an agreement. Overall, the amount of

[††] Values provided by US Corps report, and converted to tons/day with an assumed density of 2,531.05 kg/m^3

sediment in the river is decreasing in the last 50 years, while the dredging values are shown to be increasing, aside from the expansion efforts. There may be more nuance in where the dredged materials are collected and whether a larger area has been responsible for the increases. The details available could be interpreted to imply that the dredging location is being filled in with sediment from the dumping site as their reporting dredging amounts have increased, even accounting for port expansion efforts in 2004.

The depositional environments, or sediment sinks, are numerous in the shallow, tidal mud-flat areas around Cook Inlet. It is generally assumed that the Susitna Delta and Tidal flats are collecting sediment that is carried from the Knik, Susitna and Matanuska Rivers. It was hoped that with an updated model, with reasonable bathymetry and boundary inputs, this could be modeled for further review. There have been some studies that look at the beluga whale population that point to changing dynamics in the mud flats as one reason for whale strandings in the area [59].

There are several studies that point to the Shelikof Straits as the ultimate sink in the sediment budget [36]; [60]; [12]. The water is calmer, the depth is significant, and the likelihood of evaluating with samples is challenging. According to Rember and Trefry, the depositional rates measured range from 0.10-0.94 cm/year, varying based on the location in the Strait, and averaged 0.16 cm/year to 0.68 cm/year, or approximately 70% of the total riverine and erosional sediment from Cook Inlet, calculated to be about 70,000,000 tons/year [60].

4.3. Delft3D Model Results

Several iterations were required to get a model diagnosis report that was useable. Due to the nature of the Delft 3D model and Cook Inlet geometry, the model was challenging to complete. Efforts were halted due to time and resource constraints. Figure 16 shows the visualization area from Delft3D, complete with the bathymetry and observation points that were attempted to be used for output validation. The constraint at the Forelands and the related significant bathymetry changes cause the model to generate jets of water [61] that are hard for the model to overcome.

While a challenge to the model, that may actually fit well with the observed tidal rips documented around the inlet by Johnson [14]. With several rounds of finer mesh generated with local refinement, there were resilient errors and challenges. Ultimately, it was not possible to include the dredging details or the CIRCAC observations as intended. This would be helpful to see whether the particles are being resuspended and carried back by the incoming tidal forces.

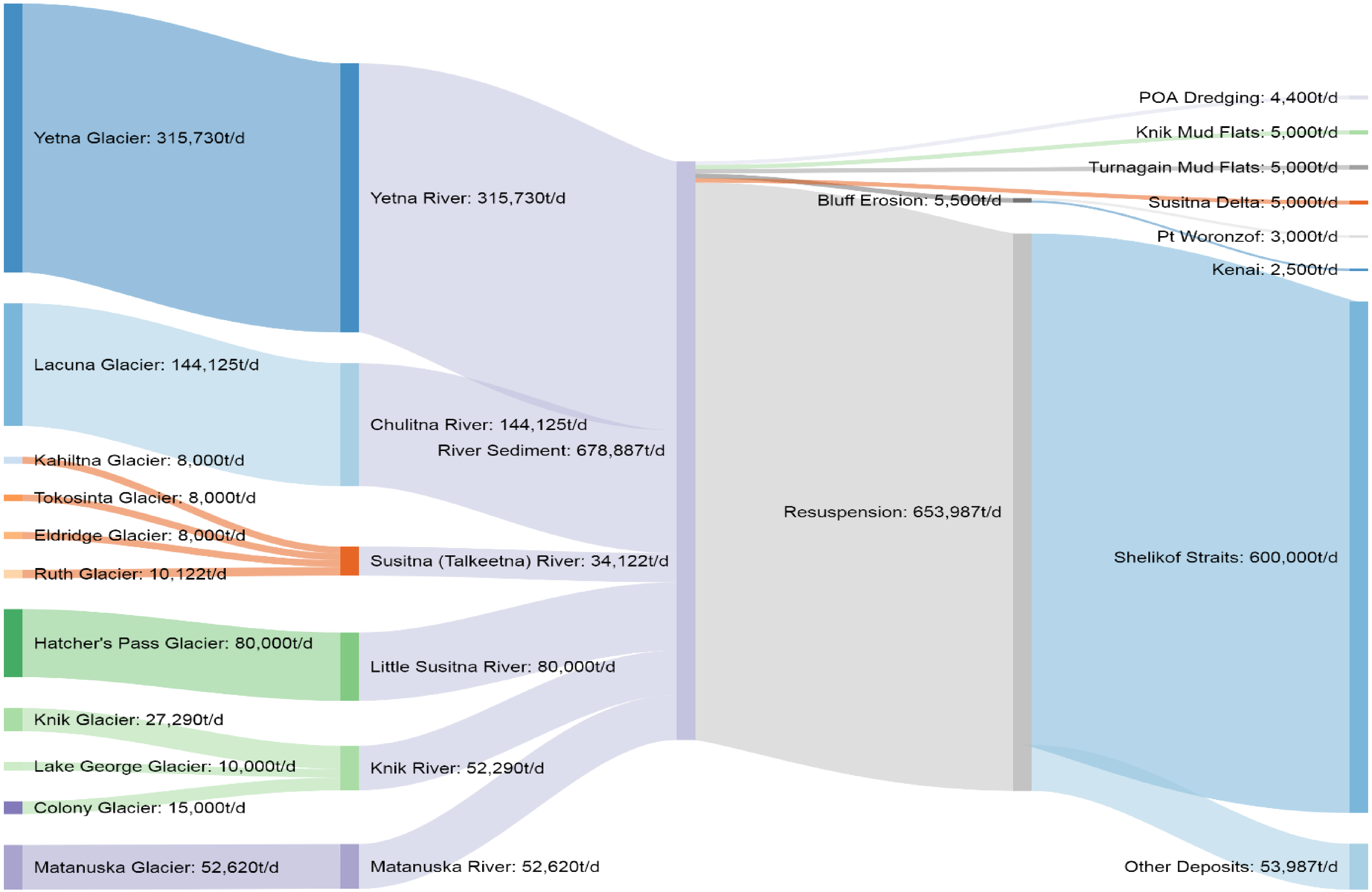


Figure 15: Sediment Budget Mass Flow Sankey Diagram, showing Cook Inlet Watershed glaciers, rivers and sediment flow (SankeyMatic) [49].

4.3. Sediment and Water Quality Modeling Results

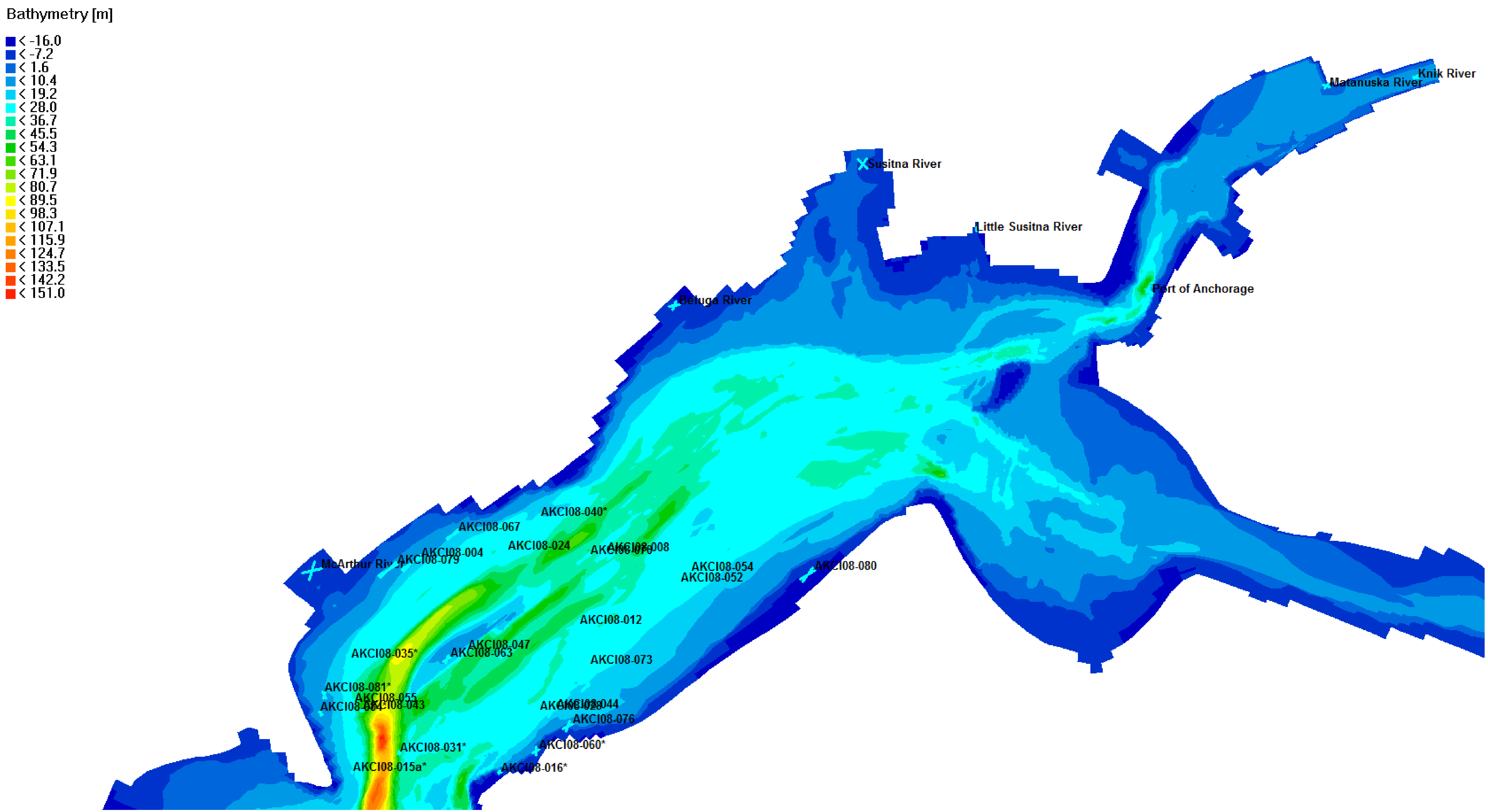


Figure 16: Delft3D Flow Model Visualization of Cook Inlet bathymetry.

Chapter 5: Summary of Findings

5.1. Cook Inlet Watershed Sediment Budget and Patterns

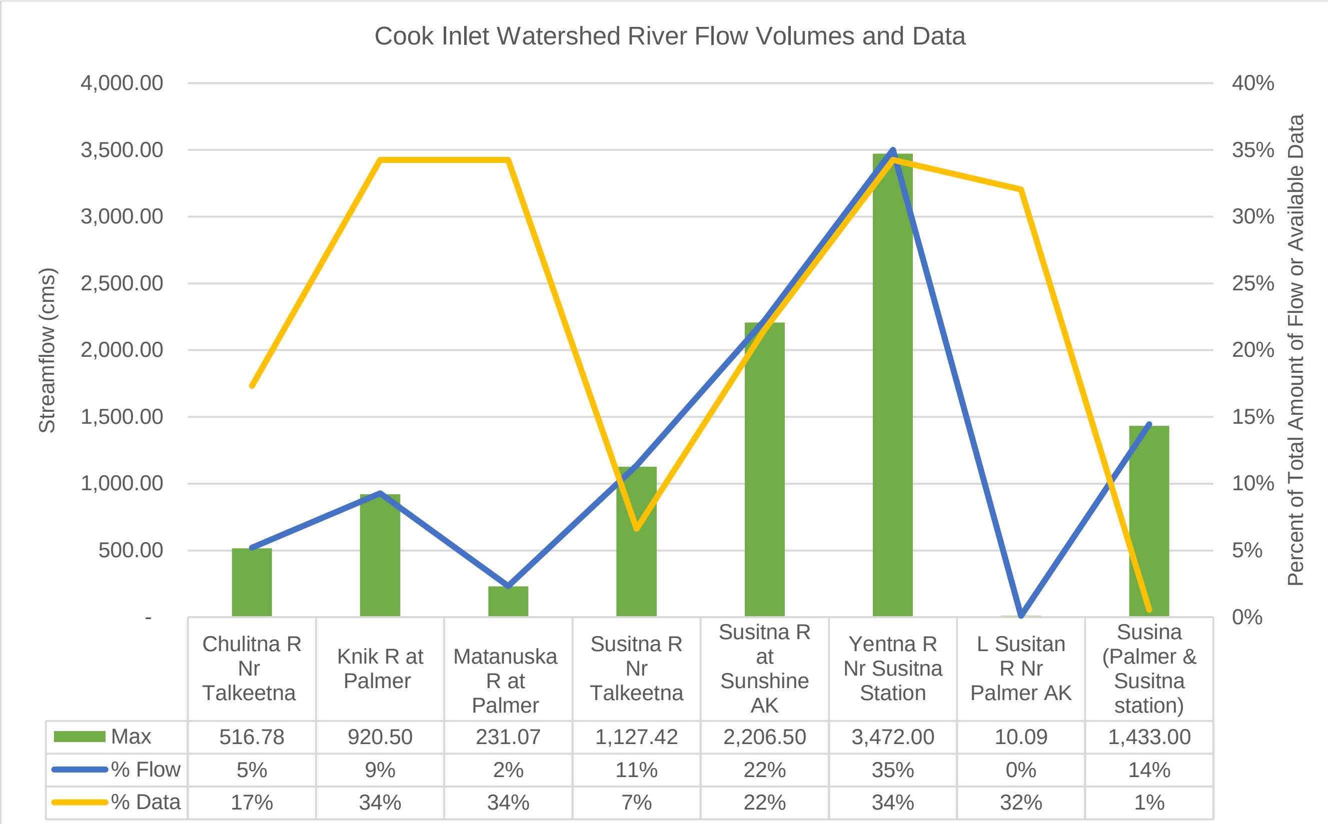
As can be seen in Figures 17 and 18 below, there are significant data for the Knik and Matanuska Rivers, though these rivers in combination only provide about 10% of the freshwater input and sediment load into Cook Inlet. Comparatively, there are very little data for the Yentna and Susitna Rivers, and these contribute approximately 50% of the freshwater and sediment to Cook Inlet.

Since 1967, the Knik River has effectively been starved of glacial sediment as George Lake has not been emptying. In part this may be due to the large earthquake that the region experienced. So, as the glaciers are melting, the rivers appear to be carrying more water, although it appears that they are not also carrying more sediment.

The data show that prior to 1964, the Knik River flooded annually when the ice dam at George Lake burst. Further, the magnitude of the floods that occurred regularly is impressive, along with the lack of flooding in the last 50 years. It looks like something indeed happened during the 1964 earthquake that somehow changed how the glacier and ice interact with the headwaters of the Knik River. The magnitude of damages is hard to estimate since not much data is available prior to 1948. The oral stories and local settlement history of Kari and Fall [22] though, would indicate that the shallow, braided nature of the Knik River allows for a large area to be impacted by flooding and further help explain why it has not been developed more. Recently, an iceberg from the neighboring Colony glacier has been adding additional ice damming to the glacial lake (Medred) [25].

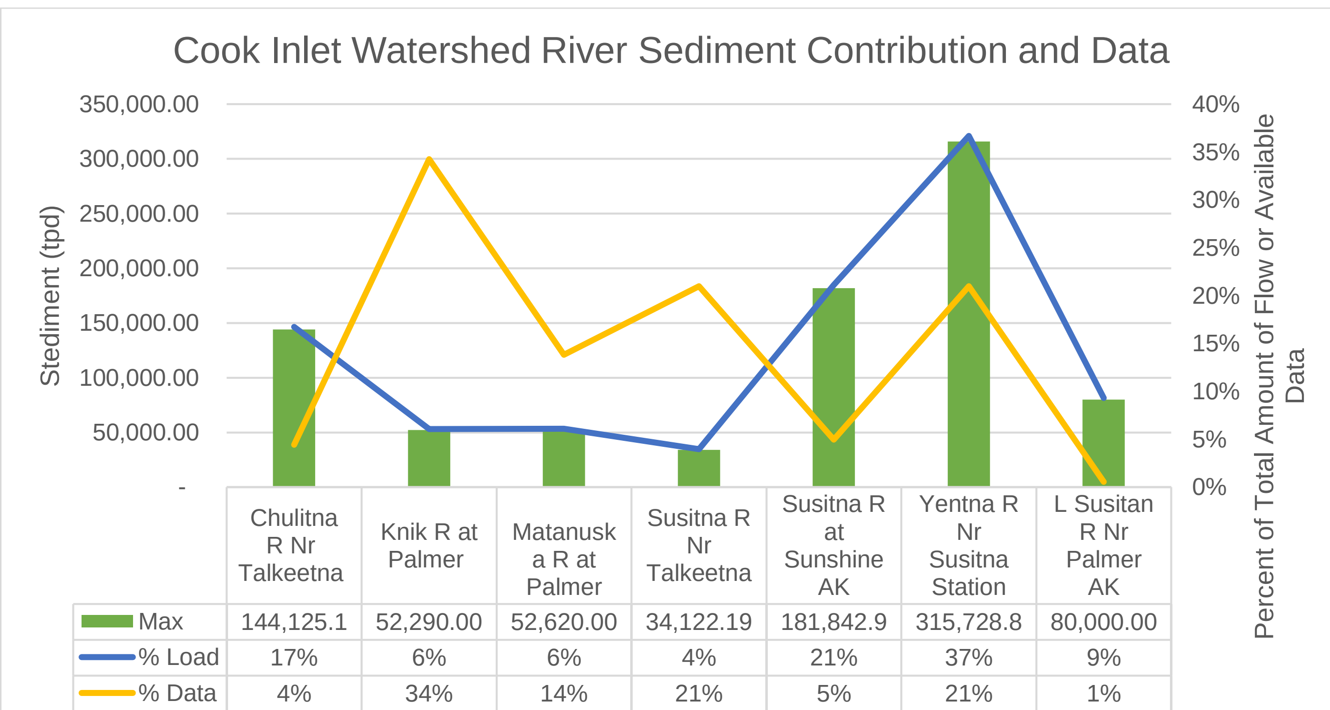
It would be good to understand better how the other rivers that flow into the Cook Inlet Watershed have changed in these last 100 years in terms of flow rates. These data are unfortunately not readily available since USGS has only recently started to gather streamflow information at some of the larger rivers.

When the river sediment data is compared for each year, by each river, with a complete set of data points, the assumption that the sediment travels from glacier to inlet could be tested. It is possible that sediment is deposited in the river before a confluence, in a delta. Of particular interest would be the sediment that flows from the Yentna into the Susitna, before their combined flow enters Cook Inlet.



	Chulitna R Nr Talkeetna	Knik R at Palmer	Matanuska R at Palmer	Susitna R Nr Talkeetna	Susitna R at Sunshine AK	Yentna R Nr Susitna Station	L Susitan R Nr Palmer AK	Susina (Palmer & Susitna station)
Max	516.78	920.50	231.07	1,127.42	2,206.50	3,472.00	10.09	1,433.00
% Flow	5%	9%	2%	11%	22%	35%	0%	14%
% Data	17%	34%	34%	7%	22%	34%	32%	1%

Figure 17: Summary Table showing relative river flow and set of available data.



	Chulitna R Nr Talkeetna	Knik R at Palmer	Matanuska R at Palmer	Susitna R Nr Talkeetna	Susitna R at Sunshine AK	Yentna R Nr Susitna Station	L Susitan R Nr Palmer AK
Max	144,125.1	52,290.00	52,620.00	34,122.19	181,842.9	315,728.8	80,000.00
% Load	17%	6%	6%	4%	21%	37%	9%
% Data	4%	34%	14%	21%	5%	21%	1%

Figure 18: Summary Table showing relative river sediment contributions and available data.

Chapter 6: Conclusions and Recommendations

Conclusion

In summary, the available data show that river flows are increasing, which compares well with documented glacial melt rates. The literature review shows several studies that further to document the dynamics of sediment and saline water in the Cook Inlet region. These demonstrate that the ocean tidal elements and river discharges are of interest to commercial shipping, industrial applications, and wildlife conservation efforts (which may be critical in the future). The river data analysis shows that for most of the rivers in Cook Inlet where there is sufficient data, the amount of water is increasing while the sediment load remains constant. This review, when comparing the Knik Arm and Port of Anchorage values, does not show a simple relationship. Instead, it appears that there is more to the circulation and resuspension of sediment in upper Cook Inlet. This dynamic sediment circulation and resuspension contains a complexity that additional modeling may help to explain. The calculated sediment inputs (or sources) along with documented and assumed depositional areas were quantified to create an updated and more complete perspective on the sediment mass balance and budget for the watershed. There are still several major rivers missing from this effort as there was not enough data available. It is visible in a mass flow diagram that some glaciers contribute more water and sediment to the watershed, and therefore the Cook Inlet water quality mix, when compared to others.

These data collections and analyses show that the Knik River was heavily influenced by the Lake George Glacier and ice dam bursts in the past. In addition, the data show that the Yentna River is the largest source of sediment to the watershed (of the rivers reviewed).

For the Port of Anchorage, it appears as though the increasing sediment amounts dredged since the 2004 port expansion effort is not related to increasing amounts of the Knik River sediment. Instead, it may be related to Ship Creek sediment or a depositional area that fills quickly, or additional sediment being moved up from the deltas or dumping site with the tide.

In addition, this effort has shown that many specific additional efforts are needed to better expand and understand the sediment budget, computer modeling, and related areas of interest such as pollutants and other impacts on sediment transport like ice and wind. Further, missing information exists in relation to the larger river flow and sediment concentrations for a complete sediment budget to be formed for the Cook Inlet watershed. Notable data gaps also exist in terms of the whole watershed assessment. Several rivers, such at the Yentna Beluga, McArthur and

Redoubt Rivers, have little to no available data. As a result, a complete budget cannot be put together yet. Additional scrutiny and attention can be put into mapping the glaciers and which rivers they flow into. This would in turn help determine the source of the sediment and also help provide data on glacial melt rates indirectly since in depth monitoring does not exist at all of the glaciers in the Cook Inlet Watershed.

In the existing USGS data, a comparative sediment dataset for larger volumes could be created since varying data types (sediment concentration and turbidity) are currently available. For example, the OBS sensors gathered data with turbidity counts near zero while out of the water when the flow was low. Is there base concentration value that could be used. A deeper review and comparison to see if values show that volumes are increasing. Quantification and assessment of the Knik River could be calculated with sediments along the river, looking specifically at the sources. Since Lake George is not emptying, are all the particles collecting at the edge of the glacier? It would also be interesting to create sediment rating curves for the Lake George ice jam flooding, or jökulhlaup events, based on what data are available, and in preparation for future events. Specifically, the years that saw significant ice dam bursts could be compared or isolated from the other data sets and evaluated. Significant risk is likely still posed by the next dam overflow event, especially since exponentially more infrastructure exists in the flood plain than in the 1960s. Details could be gathered from local pilots or guides that frequent the regions, since setting up data collection stations poses challenges.

For the Cook Inlet coastline erosion efforts, an assessment and incorporation of Kenai Peninsula erosion tracking and volumes eroded could be valuable. For example, the Kenai Peninsula Borough maintains a map tracking erosion rates along the coast, the highway, and along the Kenai River [62], which could perhaps be a source of information and comparison. Notable erosion concerns along areas of the Matanuska and Susitna Rivers and at Point McKenzie could be tabulated and included into a review of the changes over time. Overall, a missing item of information is the unknown mudflat erosion rates. Publicly available satellite remote sensing data for mudflats may be a viable option in the future. In addition, according to Eiken, quantitative use of satellite remote sensing data to map changing coastlines and morphology could be a useful means to potentially quantify the sediment transported by ice means[‡‡].

Future modeling could consider the inclusion of the Delft3D Wave module. Additional detailed evaluation of the sensitivities to boundary conditions and comparing models based on different datasets, including seasonal variability. Wind inclusion in future models may be also interesting since quite a bit of sediment is carried in the air from the braided Knik Riverbed. In terms of water quality modeling, creating a model that could show the varying stratification at depth with visualization of density would be awesome. Finally, longer simulations (years or decades instead of days) could be run to better understand seasonal impacts to sediment input and transport rates. Additional future uses of models could be better understanding of mud flat dynamics for port and infrastructure planning or maintenance or as a basis for industrial and municipal wastewater discharge modeling. Numerous parameters are found in glaciers, mountain lakes, rivers, and sediment. The mud flats existing in tidal areas that neighbor rivers create an anoxic environment that could be important in the reduction of oxic forms of mercury (Hg) to anoxic forms (e.g., Methylated mercury (CH_3Hg)). Details that are closely related to sediment transport modeling is the fate of atmospherically deposited pollutants that are bound to sediment, such as mercury and further development of the model may be used in the future as a means of tracking mercury and determining where methylation is most likely occurring.

[‡‡] A study was done to qualify sediment transported via sea ice in the Chukchi and Beaufort Seas. This report summarizes sampling efforts in the Arctic Ocean, according to Eiken (2005) [31]. Such a study has not yet been completed to cover this dynamic in relation to Cook Inlet.

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Appendix A

R Script for Sediment ANOVA Statistical Analysis

```
> full=lm(X.ton.day.~ActivityStartDate+MonitoringLocatio
nIdentifier, data=CIsediment)
> summary(CIsediment)
                     CharacteristicName
                              :535
 Sediment                     :163
 Suspended Sediment Discharge:797


 MonitoringLocationIdentifier ActivityStartDate
              :535                      :535
 USGS-15292780: 89            5/15/14: 12
 USGS-15292700: 82            5/28/14: 12
 USGS-15292100: 62            3/19/98:  9
 USGS-15294350: 62            6/26/14:  8
 USGS-15291700: 51            7/10/12:  8
 (Other)      :614            (Other):911
   X.ton.day.
 Min.   :      0.0
 1st Qu.:      4.8
 Median :    432.0
 Mean   :  31162.2
 3rd Qu.:  13700.0
 Max.   :2170000.0
 NA's   :535
```

```
> full=lm(AvgTon.Day~Year+average.flow.cfs, data=sedimentFlow)
> summary(full)

Call:
lm(formula = AvgTon.Day ~ Year + average.flow.cfs, data = sedimentFlow)

Residuals:
    Min      1Q  Median      3Q     Max
-193513   -2828   -1111    -566  161154

Coefficients:
                  Estimate Std. Error t value Pr(>|t|)
(Intercept)      -4.436e+05  8.958e+05  -0.495    0.621
Year              2.221e+02  4.470e+02   0.497    0.620
average.flow.cfs  1.139e+00  1.041e-01  10.940   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 27820 on 127 degrees of freedom
  (1434 observations deleted due to missingness)
Multiple R-squared:  0.5311,	Adjusted R-squared:  0.5238
F-statistic: 71.94 on 2 and 127 DF,  p-value: < 2.2e-16
```

```
> Flow=lm(AvgTon.Day~average.flow.cfs, data=sedimentFlow)
> summary(Flow)

Call:
lm(formula = AvgTon.Day ~ average.flow.cfs, data = sedimentFlow)

Residuals:
    Min      1Q  Median      3Q     Max
-194952   -3132   -1597   -1515  158288

Coefficients:
                  Estimate Std. Error t value Pr(>|t|)
(Intercept)      1.503e+03  2.616e+03   0.574    0.567
average.flow.cfs 1.158e+00  9.636e-02  12.020   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 27740 on 128 degrees of freedom
  (1434 observations deleted due to missingness)
Multiple R-squared:  0.5302,	Adjusted R-squared:  0.5266
F-statistic: 144.5 on 1 and 128 DF,  p-value: < 2.2e-16
```

```
> Year=lm(AvgTon.Day~Year, data=sedimentFlow)
> summary(Year)

Call:
lm(formula = AvgTon.Day ~ Year, data = sedimentFlow)

Residuals:
   Min     1Q Median     3Q    Max
-37320 -18966  -2644   -547 306963

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept) -4078108    1154961  -3.531 0.000576 ***
Year            2040        576   3.542 0.000554 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 38620 on 128 degrees of freedom
  (1434 observations deleted due to missingness)
Multiple R-squared:  0.08928,	Adjusted R-squared:  0.08216
F-statistic: 12.55 on 1 and 128 DF,  p-value: 0.0005542
```

```
> anova(Year,full)
Analysis of Variance Table

Model 1: AvgTon.Day ~ Year
Model 2: AvgTon.Day ~ Year + average.flow.cfs
  Res.Df        RSS Df  Sum of Sq      F    Pr(>F)
1    128 1.9096e+11
2    127 9.8309e+10  1 9.265e+10 119.69 < 2.2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

```
> anova(Flow,full)
Analysis of Variance Table

Model 1: AvgTon.Day ~ average.flow.cfs
Model 2: AvgTon.Day ~ Year + average.flow.cfs
  Res.Df        RSS Df Sum of Sq      F Pr(>F)
1    128 9.8500e+10
2    127 9.8309e+10  1 191065287 0.2468 0.6202
```

```
> full=lm(AvgTon.Day~Year+MonitoringLocationName, data=sediment1)
> summary(full)

Call:
lm(formula = AvgTon.Day ~ Year + MonitoringLocationName, data = sediment1)

Residuals:
   Min     1Q Median     3Q    Max
-99496  -3426      0   3415 121296

(Intercept)                                                           ***
Year                                                                  ***
MonitoringLocationNameAnchor R Nr Bald Mtn Nr Homer
MonitoringLocationNameBradley R NR Tidewater NR Homer AK
MonitoringLocationNameCamp C at Mouth Nr Colorado AK
MonitoringLocationNameCampbell C at New Seward Hwy Nr Anchorage AK
MonitoringLocationNameCampbell Creek at C St Nr Anchorage AK
MonitoringLocationNameCaribou C 0.3Mi Bl Snowshoe C Nr Kantishna
MonitoringLocationNameCaribou C 2.6Mi AB Bearpaw R Nr Kantishna
MonitoringLocationNameCaribou C 3.4Mi AB Crevice C Nr Kantishna
MonitoringLocationNameCaribou C 4.8Mi Ab Bearpaw R Nr Kantishna
MonitoringLocationNameCaribou C 7.9Mi Ab Bearpaw R Nr Kantishna
MonitoringLocationNameChakok R 7.5Mi Ab Mouth Nr Anchor Point
MonitoringLocationNameChester C at Arctic Blvd at Anchorage AK
MonitoringLocationNameChulitna R 5mi Ab Mounth Nr Port Alsworth       *
MonitoringLocationNameChulitna R Bl Canyon Nr Talkeenta               *
MonitoringLocationNameChulitna R Nr Port Alsworth
MonitoringLocationNameChulitna R Nr Talkeetna                         ***
MonitoringLocationNameSusitna R ab Tsusena C Nr Chulitna             *
MonitoringLocationNameSusitna R at Gold Creek AK                     *
MonitoringLocationNameSusitna R at Sunshine AK                       ***
MonitoringLocationNameSusitna R Nr Talkeetna                         *
MonitoringLocationNameTalkeetna R at Talkeetna                       *
MonitoringLocationNameUnnamed Tib at Port of Anchorage
MonitoringLocationNameYentna R Nr Susitna Station                    ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 30040 on 67 degrees of freedom
  (1436 observations deleted due to missingness)
Multiple R-squared:  0.7119,	Adjusted R-squared:  0.4411
F-statistic: 2.628 on 63 and 67 DF,  p-value: 6.464e-05
```

Appendix B

River Flow and Sediment Data for Analysis

	Average River Flow (m^3/s)							
Year	Chulitna R Nr Talkeetna	Knik R at Palmer	Matanuska R at Palmer	Susitna R Nr Talkeetna	Susitna R at Sunshine AK	Yentna R Nr Susitna Station	L Susitna R Nr Palmer AK	Susitna (Palmer & Susitna station)
1958	269.55	195.95	98.85			3,107.15	3.54	
1959	254.87	195.95	111.91			3,107.15	6.57	
1960	251.36	200.12	117.59			3,107.15	5.15	
1961	285.82	199.49	105.73			3,107.15	5.86	
1962	256.82	186.13	130.53			3,107.15	6.81	
1963	260.37	203.97	111.91			3,107.15	8.61	
1964	277.63	196.89	128.60			3,107.15	5.31	
1965	277.12	177.74	106.05			3,107.15	6.09	
1966	256.58	199.66	98.21			3,107.15	4.58	
1967	330.18	224.21	116.92			3,107.15	6.56	
1968	272.73	181.09	111.50			3,107.15	5.79	
1969	279.10	218.61	75.07			3,107.15	2.85	
1970	261.33	162.48	92.64			3,107.15	4.65	
1971	256.37	190.03	126.80			3,107.15	6.46	
1972	304.37	194.76	113.16			3,107.15	6.79	
1973	284.01	150.08	102.23			3,107.15	4.84	
1974	276.32	203.06	103.57			3,107.15	5.15	
1975	276.92	180.12	102.24			3,107.15	6.67	
1976	276.55	193.12	106.77			3,107.15	4.34	
1977	279.09	233.02	109.13			3,107.15	7.37	
1978	282.88	188.22	106.18			3,107.15	3.75	
1979	279.30	222.46	105.02			3,107.15	7.79	
1980	400.42	200.54	105.49			3,107.15	7.93	
1981	305.87	231.12	105.81		1127.292601	3,107.15	5.99	
1982	257.57	186.64	106.40	771.05	683.2848644	3,107.15	7.57	
1983	257.18	204.19	106.34	642.92	684.134369	3,107.15	7.20	
1984	242.78	186.30	105.87	599.31	637.4116161	3,107.15	6.22	
1985	254.33	161.15	170.31	702.85	696.8769379	3,107.15	8.70	
1986	202.16	207.51	107.13		388.2236009	3,107.15	5.15	
1987	253.32	190.46	116.97		702.87	3,107.15	5.27	1,433.00
1988	244.56	189.37	118.84		632.13	3,107.15	4.81	
1989	242.39	189.83	120.91		623.61	3,107.15	5.70	
1990	239.92	187.44	123.34		613.52	3,107.15	6.63	
1991	239.45	65.27	126.25		609.54	3,107.15	4.78	
1992	236.97	258.19	126.07		594.98	3,107.15	3.94	
1993	242.77	180.09	122.06		629.44	3,107.15	6.29	
1994	241.01	178.37	122.91		617.20	3,107.15	5.91	
1995	240.42	176.53	123.59		614.72	3,107.15	4.77	
1996	240.09	174.32	124.04		613.23	3,107.15	3.18	
1997	240.12	172.13	124.15		613.19	3,107.15	4.72	
1998	240.23	189.94	123.80		613.79	3,107.15	5.10	
1999	240.77	178.56	123.43		616.93	3,107.15	4.86	
2000	240.44	178.31	231.07		614.84	3,107.15	6.68	
2001	240.34	284.02	123.59		614.45	3,107.15	4.84	
2002	240.33	239.87	107.24		614.41	3,107.15	5.95	
2003	240.37	297.04	110.30		614.60	3,107.15	5.26	
2004	240.41	403.23	123.50		614.84	3,107.15	4.32	
2005	240.44	386.24	166.08		615.01	3,107.15	10.09	
2006	240.39	402.10	118.11		614.69	3,107.15	6.36	
2007	240.38	476.60	115.46		614.67	3,472.00	5.36	
2008	240.39	278.07	91.39		614.70	3,107.15	5.95	
2009	240.40	393.04	112.60		614.75	3,107.15	6.98	
2010	240.40	920.50	102.78		614.78	3,107.15	4.40	
2011	240.40	343.20	97.48		614.77	3,107.15	5.76	
2012	449.35	485.50	146.91	811.20	779.2788839	3,107.15	0.95	
2013	322.08	458.17	138.02	763.29	790.3224436	3,107.15	3.72	
2014	345.19	380.58	118.78	584.30	673.0908092	3,107.15	8.10	
2015	306.30	359.06	93.05	719.60	749.2630548	3,107.15	5.14	
2016	516.78	445.42	144.17	705.33	1,271.69	3,107.15		
2017	500.19	410.59	88.56	1,127.42	2,206.50	2,742.30		
2018	406.65	420.79	129.33	785.19	1,078.36	3,107.15		
2019	399.53	443.44	169.46	780.85	1132.10646	3,107.15		

	Average Sediment Load (ton/day)						
Year	Chulitna R Nr Talkeetna	Knik R at Palmer	Matanuska R at Palmer	Susitna R Nr Talkeetna	Susitna R at Sunshine AK	Yentna R Nr Susitna Station	Susitna (Palmer & Susitna station)
1958		20,547.95					
1959		20,547.95	46,950.00				
1960		20,547.95	44,650.00				
1961		20,547.95	32,160.00				
1962		52,290.00	52,620.00				
1963		35,910.00	24,690.00				
1964		16,160.00	21,010.00				
1965		18,840.00	11,100.00				
1966		29,050.00	17,720.00				
1967		28,799.66					
1968		30,174.94					
1969		26,489.10					
1970		24,918.95					
1971		26,378.78					
1972		27,635.24					
1973		27,399.44					
1974		27,166.07					
1975		26,664.60					
1976		26,693.85					
1977		26,989.66					
1978		27,091.48					
1979		27,000.85					
1980		26,934.42					
1981		26,895.81					
1982		26,934.34		31,862.00		244,225.41	
1983		26,974.43		28,321.50		243,907.19	
1984		26,971.89		23,479.00		243,554.77	
1985		26,951.96		28,743.30		243,162.60	
1986		26,943.81		28,101.45		247,194.06	
1987		26,945.37		28,101.45		246,895.16	80,000.00
1988		26,953.63		28,101.45		246,612.86	
1989		26,956.85		27,474.69		246,346.25	
1990		26,953.92		27,333.56		246,094.45	
1991		26,950.92		27,975.98		245,856.64	
1992		26,950.75		27,848.10		245,632.04	
1993		26,951.91		27,805.87		245,419.92	
1994		26,953.00		27,756.61		245,219.58	
1995		26,952.89		27,699.13		245,030.38	
1996		26,952.23		27,736.54		240,745.29	
1997		26,951.95		27,803.71		240,804.66	
1998		26,952.12		27,774.99		240,039.45	
1999		26,952.35		27,762.81		239,316.75	
2000		26,952.42		27,755.63		238,497.32	
2001		26,952.33		27,755.47		237,563.72	
2002		26,952.23		27,764.86		236,495.68	
2003		15,400.00	35,087.81	27,769.58		315,728.82	
2004		25,026.91	35,087.81	27,763.89		241,813.86	
2005		24,706.04	35,087.81	27,762.04		241,813.86	
2006		23,550.00	35,087.81	27,761.91		241,813.86	
2007		5,980.00	23,700.00	27,762.96		241,813.86	
2008		20,269.20	32,810.25	27,764.21		241,813.86	
2009		19,155.36	32,810.25	27,764.10		241,813.86	
2010		19,781.25	32,430.65	27,763.18		241,813.86	
2011		18,906.97	31,987.80	27,763.07	925.00	241,813.86	
2012	144,125.13	17,940.46	31,471.13	16,917.76	181,842.93	241,813.86	
2013	82,720.00	17,005.54	30,868.35	34,122.19	123,728.00	167,898.89	
2014	43,297.26	18,843.13	32,063.07	8,658.62	54,207.84	241,813.86	
2015	90,047.46	18,605.45	31,938.54	23,831.49	90,175.94	227,030.86	
2016	90,047.46	18,513.80	31,793.25	23,176.05	90,175.94	227,030.86	
2017	90,047.46	18,302.56	31,687.02	22,411.53	90,175.94	224,567.03	
2018	90,047.46	18,201.82	31,636.89	21,519.61	105,051.10	221,692.56	
2019	81,034.52	18,245.38	31,664.52	22,286.58	92,252.46	218,339.01	

Data Interpretation Key and References	#	Comment	
Average of 1958-1966 water years (USGS, 1959-1997)	24		
Calculated from monthly data (USGS)	24		
Running average of previous data - 6 years			
Running average of available data			
Converted from Turbidity readings, NTU	24		
Average of grouped average of available data averaged	24		
KABATA 2007 Kinnetic laboratories report	37		
Port of Anchorage, Jon Zufelt report/graphs			
CIRCAC 2008 data	11		

Appendix C

Sankey Diagram code

```
<svg id="sankey_svg" height="600" width="750" xmlns="http://www.w3.org/2000/svg"
version="1.1"><title>Your Diagram Title</title><!-- Generated with SankeyMATIC on Fri Sep 11 2020 09:21:53
GMT-0800 (Alaska Daylight Time)--><g><rect width="100%" height="100%" fill="rgb(255, 255,
255)"></rect><g transform="translate(12,12)"><g><path class="link"
d="M368,297.49949770040877C427.15,297.49949770040877 477.85,330.5804872612439
537,330.5804872612439" style="fill: none; stroke-width: 362.209; stroke: rgb(189, 189, 189); stroke-opacity:
0.5;"><title>River Sediment &#8594; Resuspension:
653,987t/d</title></path><path class="link" d="M547,315.63019951085244C606.15,315.63019951085244
656.85,359.94511605024104 716,359.94511605024104" style="fill: none; stroke-width: 332.309; stroke: rgb(107,
174, 214); stroke-opacity: 0.5;"><title>Resuspension &#8594; Shelikof Straits:
600,000t/d</title></path><path class="link" d="M10,87.43316634432531C69.15,87.43316634432531
119.85000000000001,126.38026996409462 179,126.38026996409462" style="fill: none; stroke-width: 174.866;
stroke: rgb(49, 130, 189); stroke-opacity: 0.5;"><title>Yentna Glacier &#8594; Yentna River:
315,730t/d</title></path><path class="link" d="M189,126.38026996409462C248.15,126.38026996409462
298.85,190.0372602441016 358,190.0372602441016" style="fill: none; stroke-width: 174.866; stroke: rgb(188,
189, 220); stroke-opacity: 0.5;"><title>Yentna River &#8594; River Sediment:
315,730t/d</title></path><path class="link" d="M10,234.77798219733177C69.15,234.77798219733177
119.85000000000001,273.7250858171011 179,273.7250858171011" style="fill: none; stroke-width: 79.8233;
stroke: rgb(158, 202, 225); stroke-opacity: 0.5;"><title>Lacuna Glacier &#8594; Chulitna River:
144,125t/d</title></path><path class="link" d="M189,273.7250858171011C248.15,273.7250858171011
298.85,317.38207609710804 358,317.38207609710804" style="fill: none; stroke-width: 79.8233; stroke: rgb(188,
189, 220); stroke-opacity: 0.5;"><title>Chulitna River &#8594; River Sediment:
144,125t/d</title></path><path class="link" d="M10,415.74193054219626C69.15,415.74193054219626
119.85000000000001,430.98939819021774 179,430.98939819021774" style="fill: none; stroke-width: 44.3078;
stroke: rgb(116, 196, 118); stroke-opacity: 0.5;"><title>Hatcher's Pass Glacier &#8594; Little Susitna River:
80,000t/d</title></path><path class="link" d="M189,430.98939819021774C248.15,430.98939819021774
298.85,398.34602444197253 358,398.34602444197253" style="fill: none; stroke-width: 44.3078; stroke: rgb(188,
189, 220); stroke-opacity: 0.5;"><title>Little Susitna River &#8594; River Sediment:
80,000t/d</title></path><path class="link" d="M547,496.73479571021994C606.15,496.73479571021994
656.85,561.0497122496085 716,561.0497122496085" style="fill: none; stroke-width: 29.9006; stroke: rgb(158,
202, 225); stroke-opacity: 0.5;"><title>Resuspension &#8594; Other Deposits:
53,987t/d</title></path><path class="link" d="M10,561.4282671490248C69.15,561.4282671490248
119.85000000000001,560.8759774825477 179,560.8759774825477" style="fill: none; stroke-width: 29.1435;
stroke: rgb(158, 154, 200); stroke-opacity: 0.5;"><title>Matanuska Glacier &#8594; Matanuska River:
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52,620t/d</title></path><path class="link" d="M189,560.8759774825477C248.15,560.8759774825477
298.85,464.03236104880114 358,464.03236104880114" style="fill: none; stroke-width: 29.1435; stroke: rgb(188,
189, 220); stroke-opacity: 0.5;"><title>Matanuska River → River Sediment:
52,620t/d</title></path><path class="link" d="M189,496.8798186943283C248.15,496.8798186943283
298.85,434.9802802164976 358,434.9802802164976" style="fill: none; stroke-width: 28.9607; stroke: rgb(188,
189, 220); stroke-opacity: 0.5;"><title>Knik River → River Sediment:
52,290t/d</title></path><path class="link" d="M189,362.3648475848637C248.15,362.3648475848637
298.85,366.74292112728244 358,366.74292112728244" style="fill: none; stroke-width: 18.8984; stroke: rgb(188,
189, 220); stroke-opacity: 0.5;"><title>Susitna (Talkeetna) River → River Sediment:
34,122t/d</title></path><path class="link" d="M10,465.45309013134727C69.15,465.45309013134727
119.85000000000001,489.95672250895433 179,489.95672250895433" style="fill: none; stroke-width: 15.1145;
stroke: rgb(161, 217, 155); stroke-opacity: 0.5;"><title>Knik Glacier → Knik River:
27,290t/d</title></path><path class="link" d="M10,522.7026765868252C69.15,522.7026765868252
119.85000000000001,507.2063089644322 179,507.2063089644322" style="fill: none; stroke-width: 8.30772;
stroke: rgb(161, 217, 155); stroke-opacity: 0.5;"><title>Colony Glacier → Knik River:
15,000t/d</title></path><path class="link" d="M10,370.78499956546517C69.15,370.78499956546517
119.85000000000001,369.0110199228227 179,369.0110199228227" style="fill: none; stroke-width: 5.60605;
stroke: rgb(230, 85, 13); stroke-opacity: 0.5;"><title>Ruth Glacier → Susitna (Talkeetna) River:
10,122t/d</title></path><path class="link" d="M10,495.77958040145114C69.15,495.77958040145114
119.85000000000001,500.2832127790582 179,500.2832127790582" style="fill: none; stroke-width: 5.53848;
stroke: rgb(161, 217, 155); stroke-opacity: 0.5;"><title>Lake George Glacier → Knik River:
10,000t/d</title></path><path class="link" d="M10,296.9050224853326C69.15,296.9050224853326
119.85000000000001,355.13104284269014 179,355.13104284269014" style="fill: none; stroke-width: 4.43078;
stroke: rgb(230, 85, 13); stroke-opacity: 0.5;"><title>Kahiltna Glacier → Susitna (Talkeetna) River:
8,000t/d</title></path><path class="link" d="M10,321.33580404397196C69.15,321.33580404397196
119.85000000000001,359.5618244013295 179,359.5618244013295" style="fill: none; stroke-width: 4.43078;
stroke: rgb(230, 85, 13); stroke-opacity: 0.5;"><title>Tokosinta Glacier → Susitna (Talkeetna) River:
8,000t/d</title></path><path class="link" d="M10,345.7665856026113C69.15,345.7665856026113
119.85000000000001,363.99260595996884 179,363.99260595996884" style="fill: none; stroke-width: 4.43078;
stroke: rgb(230, 85, 13); stroke-opacity: 0.5;"><title>Eldridge Glacier → Susitna (Talkeetna) River:
8,000t/d</title></path><path class="link" d="M368,112.10258186610938C427.15,112.10258186610938
477.85,127.95280990109411 537,127.95280990109411" style="fill: none; stroke-width: 3.04616; stroke: rgb(99,
99, 99); stroke-opacity: 0.5;"><title>River Sediment → Bluff Erosion:
5,500t/d</title></path><path class="link" d="M368,106.4256429941027C489.8,106.4256429941027
594.2,83.82154909432643 716,83.82154909432643" style="fill: none; stroke-width: 2.76924; stroke: rgb(161, 217,
155); stroke-opacity: 0.5;"><title>River Sediment → Knik Mud Flats:
5,000t/d</title></path><path class="link" d="M368,109.19488146825229C489.8,109.19488146825229

594.2,106.59078756847602 716,106.59078756847602" style="fill: none; stroke-width: 2.76924; stroke: rgb(150, 150, 150); stroke-opacity: 0.5;"><title>River Sediment → Turnagain Mud Flats: 5,000t/d</title></path><path class="link" d="M368,115.01028226396646C489.8,115.01028226396646 594.2,129.3600260426256 716,129.3600260426256" style="fill: none; stroke-width: 2.76924; stroke: rgb(230, 85, 13); stroke-opacity: 0.5;"><title>River Sediment → Susitna Delta: 5,000t/d</title></path><path class="link" d="M368,103.82255882840207C489.8,103.82255882840207 594.2,61.2184649286258 716,61.2184649286258" style="fill: none; stroke-width: 2.43693; stroke: rgb(218, 218, 235); stroke-opacity: 0.5;"><title>River Sediment → POA Dredging: 4,400t/d</title></path><path class="link" d="M547,127.2605002825567C606.15,127.2605002825567 656.85,151.5754168219453 716,151.5754168219453" style="fill: none; stroke-width: 1.66154; stroke: rgb(217, 217, 217); stroke-opacity: 0.5;"><title>Bluff Erosion → Pt Woronzof: 3,000t/d</title></path><path class="link" d="M547,128.783581443339C606.15,128.783581443339 656.85,173.09849798272757 716,173.09849798272757" style="fill: none; stroke-width: 1.38462; stroke: rgb(49, 130, 189); stroke-opacity: 0.5;"><title>Bluff Erosion → Kenai: 2,500t/d</title></path></g><g><g class="node" transform="translate(0,-3.552713678800501e-14)"><rect height="174.8663326886507" width="10" id="r0" shape-rendering="crispEdges" style="fill: rgb(49, 130, 189); fill-opacity: 0.9; stroke-width: 0; stroke: rgb(24, 63, 92);"><title>Yentna Glacier: 315,730t/d</title></rect><text x="16" y="87.43316634432534" dy=".35em" text-anchor="start" style="stroke-width: 0; font-family: sans-serif; font-size: 10px; font-weight: 400; fill: rgb(0, 0, 0);">Yentna Glacier: 315,730t/d</text></g><g class="node" transform="translate(179,38.94710361976928)"><rect height="174.8663326886507" width="10" id="r1" shape-rendering="crispEdges" style="fill: rgb(49, 130, 189); fill-opacity: 0.9; stroke-width: 0; stroke: rgb(24, 63, 92);"><title>Yentna River: 315,730t/d</title></rect><text x="16" y="87.43316634432534" dy=".35em" text-anchor="start" style="stroke-width: 0; font-family: sans-serif; font-size: 10px; font-weight: 400; fill: rgb(0, 0, 0);">Yentna River: 315,730t/d</text></g><g class="node" transform="translate(0,194.86633268865066)"><rect height="79.82329901736225" width="10" id="r2" shape-rendering="crispEdges" style="fill: rgb(107, 174, 214); fill-opacity: 0.9; stroke-width: 0; stroke: rgb(52, 85, 104);"><title>Lacuna Glacier: 144,125t/d</title></rect><text x="16" y="39.91164950868112" dy=".35em" text-anchor="start" style="stroke-width: 0; font-family: sans-serif; font-size: 10px; font-weight: 400; fill: rgb(0, 0, 0);">Lacuna Glacier: 144,125t/d</text></g><g class="node" transform="translate(179,233.81343630841997)"><rect height="79.82329901736225" width="10" id="r3" shape-rendering="crispEdges" style="fill: rgb(158, 202, 225); fill-opacity: 0.9; stroke-width: 0; stroke: rgb(77, 98, 110);"><title>Chulitna River: 144,125t/d</title></rect><text x="16" y="39.91164950868112" dy=".35em" text-anchor="start" style="stroke-width: 0; font-family: sans-serif; font-size: 10px; font-weight: 400; fill: rgb(0, 0, 0);">Chulitna River: 144,125t/d</text></g><g class="node" transform="translate(0,294.6896317060129)"><rect height="4.430781558639361" width="10" id="r4" shape-rendering="crispEdges" style="fill: rgb(198, 219, 239); fill-opacity: 0.9; stroke-width: 0; stroke: rgb(97, 107, 117);"><title>Kahiltna Glacier:

8,000t/d</title></rect><text x="16" y="2.2153907793196805" dy=".35em" text-anchor="start" style="stroke-width: 0; font-family: sans-serif; font-size: 10px; font-weight: 400; fill: rgb(0, 0, 0);">Kahiltna Glacier: 8,000t/d</text></g><g class="node" transform="translate(179,352.91565206337043)"><rect height="18.898391042986535" width="10" id="r5" shape-rendering="crispEdges" style="fill: rgb(230, 85, 13); fill-opacity: 0.9; stroke-width: 0; stroke: rgb(112, 41, 6);"><title>Susitna (Talkeetna) River: 34,122t/d</title></rect><text x="16" y="9.449195521493268" dy=".35em" text-anchor="start" style="stroke-width: 0; font-family: sans-serif; font-size: 10px; font-weight: 400; fill: rgb(0, 0, 0);">Susitna (Talkeetna) River: 34,122t/d</text></g><g class="node" transform="translate(0,319.12041326465226)"><rect height="4.430781558639361" width="10" id="r6" shape-rendering="crispEdges" style="fill: rgb(253, 141, 60); fill-opacity: 0.9; stroke-width: 0; stroke: rgb(123, 69, 29);"><title>Tokosinta Glacier: 8,000t/d</title></rect><text x="16" y="2.2153907793196805" dy=".35em" text-anchor="start" style="stroke-width: 0; font-family: sans-serif; font-size: 10px; font-weight: 400; fill: rgb(0, 0, 0);">Tokosinta Glacier: 8,000t/d</text></g><g class="node" transform="translate(0,343.5511948232916)"><rect height="4.430781558639361" width="10" id="r7" shape-rendering="crispEdges" style="fill: rgb(253, 174, 107); fill-opacity: 0.9; stroke-width: 0; stroke: rgb(123, 85, 52);"><title>Eldridge Glacier: 8,000t/d</title></rect><text x="16" y="2.2153907793196805" dy=".35em" text-anchor="start" style="stroke-width: 0; font-family: sans-serif; font-size: 10px; font-weight: 400; fill: rgb(0, 0, 0);">Eldridge Glacier: 8,000t/d</text></g><g class="node" transform="translate(0,367.98197638193096)"><rect height="5.606046367068452" width="10" id="r8" shape-rendering="crispEdges" style="fill: rgb(253, 208, 162); fill-opacity: 0.9; stroke-width: 0; stroke: rgb(123, 101, 79);"><title>Ruth Glacier: 10,122t/d</title></rect><text x="16" y="2.803023183534226" dy=".35em" text-anchor="start" style="stroke-width: 0; font-family: sans-serif; font-size: 10px; font-weight: 400; fill: rgb(0, 0, 0);">Ruth Glacier: 10,122t/d</text></g><g class="node" transform="translate(0,393.58802274899944)"><rect height="44.307815586393616" width="10" id="r9" shape-rendering="crispEdges" style="fill: rgb(49, 163, 84); fill-opacity: 0.9; stroke-width: 0; stroke: rgb(24, 79, 41);"><title>Hatcher's Pass Glacier: 80,000t/d</title></rect><text x="16" y="22.153907793196808" dy=".35em" text-anchor="start" style="stroke-width: 0; font-family: sans-serif; font-size: 10px; font-weight: 400; fill: rgb(0, 0, 0);">Hatcher's Pass Glacier: 80,000t/d</text></g><g class="node" transform="translate(179,408.8354903970209)"><rect height="44.307815586393616" width="10" id="r10" shape-rendering="crispEdges" style="fill: rgb(116, 196, 118); fill-opacity: 0.9; stroke-width: 0; stroke: rgb(56, 96, 57);"><title>Little Susitna River: 80,000t/d</title></rect><text x="16" y="22.153907793196808" dy=".35em" text-anchor="start" style="stroke-width: 0; font-family: sans-serif; font-size: 10px; font-weight: 400; fill: rgb(0, 0, 0);">Little Susitna River: 80,000t/d</text></g><g class="node" transform="translate(0,457.895838335393)"><rect height="15.114503591908521" width="10" id="r11" shape-rendering="crispEdges" style="fill: rgb(161, 217, 155); fill-opacity: 0.9; stroke-width: 0; stroke: rgb(78, 106, 75);"><title>Knik Glacier: 27,290t/d</title></rect><text x="16" y="7.557251795954261" dy=".35em" text-anchor="start" style="stroke-width: 0; font-family: sans-serif; font-size: 10px; font-weight: 400; fill: rgb(0, 0, 0);">Knik Glacier:

27,290t/d</text></g><g class="node" transform="translate(179,482.3994707130001)"><rect
height="28.960695962656526" width="10" id="r12" shape-rendering="crispEdges" style="fill: rgb(161, 217, 155);
fill-opacity: 0.9; stroke-width: 0; stroke: rgb(78, 106, 75);"><title>Knik River:
52,290t/d</title></rect><text x="16" y="14.480347981328263" dy=".35em" text-anchor="start" style="stroke-
width: 0; font-family: sans-serif; font-size: 10px; font-weight: 400; fill: rgb(0, 0, 0);">Knik River:
52,290t/d</text></g><g class="node" transform="translate(0,493.01034192730157)"><rect
height="5.538476948299202" width="10" id="r13" shape-rendering="crispEdges" style="fill: rgb(199, 233, 192);
fill-opacity: 0.9; stroke-width: 0; stroke: rgb(97, 114, 94);"><title>Lake George Glacier:
10,000t/d</title></rect><text x="16" y="2.769238474149601" dy=".35em" text-anchor="start" style="stroke-width:
0; font-family: sans-serif; font-size: 10px; font-weight: 400; fill: rgb(0, 0, 0);">Lake George Glacier:
10,000t/d</text></g><g class="node" transform="translate(0,518.5488188756008)"><rect
height="8.307715422448803" width="10" id="r14" shape-rendering="crispEdges" style="fill: rgb(117, 107, 177);
fill-opacity: 0.9; stroke-width: 0; stroke: rgb(57, 52, 86);"><title>Colony Glacier:
15,000t/d</title></rect><text x="16" y="4.1538577112244015" dy=".35em" text-anchor="start" style="stroke-
width: 0; font-family: sans-serif; font-size: 10px; font-weight: 400; fill: rgb(0, 0, 0);">Colony Glacier:
15,000t/d</text></g><g class="node" transform="translate(0,546.8565342980496)"><rect
height="29.143465701950397" width="10" id="r15" shape-rendering="crispEdges" style="fill: rgb(158, 154, 200);
fill-opacity: 0.9; stroke-width: 0; stroke: rgb(77, 75, 97);"><title>Matanuska Glacier:
52,620t/d</title></rect><text x="16" y="14.571732850975199" dy=".35em" text-anchor="start" style="stroke-
width: 0; font-family: sans-serif; font-size: 10px; font-weight: 400; fill: rgb(0, 0, 0);">Matanuska Glacier:
52,620t/d</text></g><g class="node" transform="translate(179,546.3042446315725)"><rect
height="29.143465701950397" width="10" id="r16" shape-rendering="crispEdges" style="fill: rgb(158, 154, 200);
fill-opacity: 0.9; stroke-width: 0; stroke: rgb(77, 75, 97);"><title>Matanuska River:
52,620t/d</title></rect><text x="16" y="14.571732850975199" dy=".35em" text-anchor="start" style="stroke-
width: 0; font-family: sans-serif; font-size: 10px; font-weight: 400; fill: rgb(0, 0, 0);">Matanuska River:
52,620t/d</text></g><g class="node" transform="translate(358,102.60409389977625)"><rect height="376"
width="10" id="r17" shape-rendering="crispEdges" style="fill: rgb(188, 189, 220); fill-opacity: 0.9; stroke-width: 0;
stroke: rgb(92, 92, 107);"><title>River Sediment:
678,887t/d</title></rect><text x="-6" y="188" dy=".35em" text-anchor="end" style="stroke-width: 0; font-family:
sans-serif; font-size: 10px; font-weight: 400; fill: rgb(0, 0, 0);">River Sediment: 678,887t/d</text></g><g
class="node" transform="translate(716,59.99999999999997)"><rect height="2.436929857251649" width="10"
id="r18" shape-rendering="crispEdges" style="fill: rgb(218, 218, 235); fill-opacity: 0.9; stroke-width: 0; stroke:
rgb(106, 106, 115);"><title>POA Dredging:
4,400t/d</title></rect><text x="-6" y="1.2184649286258245" dy=".35em" text-anchor="end" style="stroke-width:
0; font-family: sans-serif; font-size: 10px; font-weight: 400; fill: rgb(0, 0, 0);">POA Dredging:
4,400t/d</text></g><g class="node" transform="translate(537,126.42972874031183)"><rect
height="3.046162321564561" width="10" id="r19" shape-rendering="crispEdges" style="fill: rgb(99, 99, 99); fill-

opacity: 0.9; stroke-width: 0; stroke: rgb(48, 48, 48);"><title>Bluff Erosion: 5,500t/d</title></rect><text x="-6" y="1.5230811607822805" dy=".35em" text-anchor="end" style="stroke-width: 0; font-family: sans-serif; font-size: 10px; font-weight: 400; fill: rgb(0, 0, 0);">Bluff Erosion: 5,500t/d</text></g><g class="node" transform="translate(716,82.43692985725163)"><rect height="2.769238474149601" width="10" id="r20" shape-rendering="crispEdges" style="fill: rgb(161, 217, 155); fill-opacity: 0.9; stroke-width: 0; stroke: rgb(78, 106, 75);"><title>Knik Mud Flats: 5,000t/d</title></rect><text x="-6" y="1.3846192370748005" dy=".35em" text-anchor="end" style="stroke-width: 0; font-family: sans-serif; font-size: 10px; font-weight: 400; fill: rgb(0, 0, 0);">Knik Mud Flats: 5,000t/d</text></g><g class="node" transform="translate(716,105.20616833140122)"><rect height="2.769238474149601" width="10" id="r21" shape-rendering="crispEdges" style="fill: rgb(150, 150, 150); fill-opacity: 0.9; stroke-width: 0; stroke: rgb(73, 73, 73);"><title>Turnagain Mud Flats: 5,000t/d</title></rect><text x="-6" y="1.3846192370748005" dy=".35em" text-anchor="end" style="stroke-width: 0; font-family: sans-serif; font-size: 10px; font-weight: 400; fill: rgb(0, 0, 0);">Turnagain Mud Flats: 5,000t/d</text></g><g class="node" transform="translate(716,127.97540680555082)"><rect height="2.769238474149601" width="10" id="r22" shape-rendering="crispEdges" style="fill: rgb(230, 85, 13); fill-opacity: 0.9; stroke-width: 0; stroke: rgb(112, 41, 6);"><title>Susitna Delta: 5,000t/d</title></rect><text x="-6" y="1.3846192370748005" dy=".35em" text-anchor="end" style="stroke-width: 0; font-family: sans-serif; font-size: 10px; font-weight: 400; fill: rgb(0, 0, 0);">Susitna Delta: 5,000t/d</text></g><g class="node" transform="translate(537,149.47589106187638)"><rect height="362.209192398735" width="10" id="r23" shape-rendering="crispEdges" style="fill: rgb(189, 189, 189); fill-opacity: 0.9; stroke-width: 0; stroke: rgb(92, 92, 92);"><title>Resuspension: 653,987t/d</title></rect><text x="-6" y="181.1045961993675" dy=".35em" text-anchor="end" style="stroke-width: 0; font-family: sans-serif; font-size: 10px; font-weight: 400; fill: rgb(0, 0, 0);">Resuspension: 653,987t/d</text></g><g class="node" transform="translate(716,150.74464527970042)"><rect height="1.6615430844897605" width="10" id="r24" shape-rendering="crispEdges" style="fill: rgb(217, 217, 217); fill-opacity: 0.9; stroke-width: 0; stroke: rgb(106, 106, 106);"><title>Pt Woronzof: 3,000t/d</title></rect><text x="-6" y="0.8307715422448803" dy=".35em" text-anchor="end" style="stroke-width: 0; font-family: sans-serif; font-size: 10px; font-weight: 400; fill: rgb(0, 0, 0);">Pt Woronzof: 3,000t/d</text></g><g class="node" transform="translate(716,172.40618836419017)"><rect height="1.3846192370748005" width="10" id="r25" shape-rendering="crispEdges" style="fill: rgb(49, 130, 189); fill-opacity: 0.9; stroke-width: 0; stroke: rgb(24, 63, 92);"><title>Kenai: 2,500t/d</title></rect><text x="-6" y="0.6923096185374003" dy=".35em" text-anchor="end" style="stroke-width: 0; font-family: sans-serif; font-size: 10px; font-weight: 400; fill: rgb(0, 0, 0);">Kenai: 2,500t/d</text></g><g class="node" transform="translate(716,193.79080760126496)"><rect height="332.3086168979521" width="10" id="r26" shape-rendering="crispEdges" style="fill: rgb(107, 174, 214); fill-opacity: 0.9; stroke-width: 0; stroke: rgb(52, 85, 104);"><title>Shelikof Straits: 600,000t/d</title></rect><text x="-6" y="166.15430844897605" dy=".35em" text-anchor="end" style="stroke-

width: 0; font-family: sans-serif; font-size: 10px; font-weight: 400; fill: rgb(0, 0, 0);">Shelikof Straits: 600,000t/d</text></g><g class="node" transform="translate(716,546.0994244992171)"><rect height="29.9005755007829" width="10" id="r27" shape-rendering="crispEdges" style="fill: rgb(158, 202, 225); fill-opacity: 0.9; stroke-width: 0; stroke: rgb(77, 98, 110);"><title>Other Deposits: 53,987t/d</title></rect><text x="-6" y="14.95028775039145" dy=".35em" text-anchor="end" style="stroke-width: 0; font-family: sans-serif; font-size: 10px; font-weight: 400; fill: rgb(0, 0, 0);">Other Deposits: 53,987t/d</text></g></g></g></g></svg>